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Enabling Fairness and QoS for LTE/Wi-Fi Coexistence in Unlicensed Spectrum

Master of Science Thesis

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ABSTRACT

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The increase of the number of interconnected devices, the Internet of Things (IoT) and new types of services have led to the development of new techniques to improve data transmission and new commercial opportunities in the telecommunications world.

A possible solution that has attracted many telecom companies is the ability to expand their business by exploring new frequency bands, in particular the unlicensed spectrum.

Licensed Assisted Access (LAA) is an LTE based technology that leverages the 5GHz unlicensed band along with licensed spectrum to deliver a performance boost for mobile device users.

A key aspect of LAA is how to regulate access to the communication channel in order to maintain fairness between LTE and other technologies already present in this spectrum section.

Listen Before Talk (LBT) is a technique used in radiocommunications whereby radio transmitters first sense its radio environment before it starts a transmission. However, the aggressive character of LTE is not always correctly managed by LBT.

Based on this observation, we have tried to develop a new channel access method that makes LTE less invasive on the unlicensed spectrum, providing high performance services.

The results obtained show that our algorithm is able to better balance resource sharing by ensuring that all technologies within the frequency band have good coexistence and high performance.

Preface

This Master thesis was written at Tampere University of Technology, Tampere, Finland during the period of September 2016 –June 2017.

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I am grateful to my family for their precious support and encouragements during hard times throughout this period. They have taught me what does love and support really mean.

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Tampere, August 2017

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1. Introduction

1.1 State of the art

Technologies are emerging and affecting our lives in ways that indicate we are at the beginning of a fourth Industrial Revolution, a new era that builds and extends the impact of digitization in new and unanticipated ways.

Technology has played a big role in the development of various industries, it has changed the banking sector, changed education, changed the agricultural industry, changed the entertainment word, in has restructured many businesses.

Within the telecommunications sector, the wide spread adoption of smart phones, IoT devices and availability of easily downloadable free and paid applications continues to drive the increase in data and signaling volume on mobile networks.

According to the leading telecommunications companies:

- Between 2015 and 2021, IoT is expected to increase at a compounded annual growth rate of 23 percent, making up close to 16 billion of the total forecast 28 billion connected devices in 2021.
- Mobile subscriptions are growing around 3 percent year-on-year globally and reached 7.4 billion in Q1 2016. Mobile broadband subscriptions are growing by around 20 percent year-on-year, increasing by approximately 140 million in Q1 2016 alone.

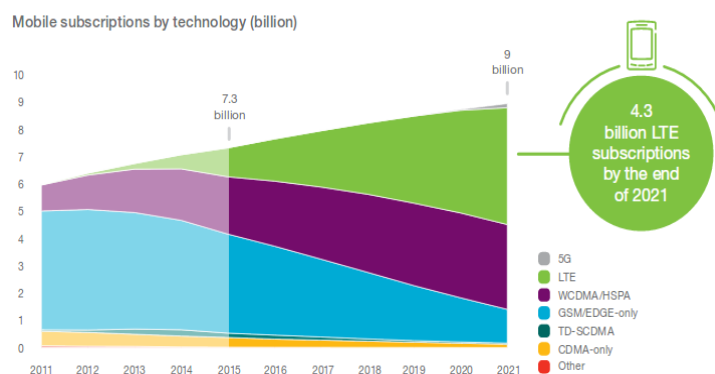


Figure 1 Technology Evolution

Applications on smart phones periodically connect and disconnect to/from the network for updates. Each connection/disconnection attempt requires several message exchanges between the smart phone and the network. All these message exchanges generate signaling load on the network. This signaling load becomes a costly overhead especially when the amount of data per connection is relatively small as in the case of many common applications such as news, weather, social networking, etc. This ever-increasing data and

signaling load puts a strain on the operators' network.

Moreover, the type and quality standards of data traffic are changing. The emergence of new applications can shift the relative volumes of different types of traffic, but the proliferation of different sized smart devices will also affect the traffic mix.

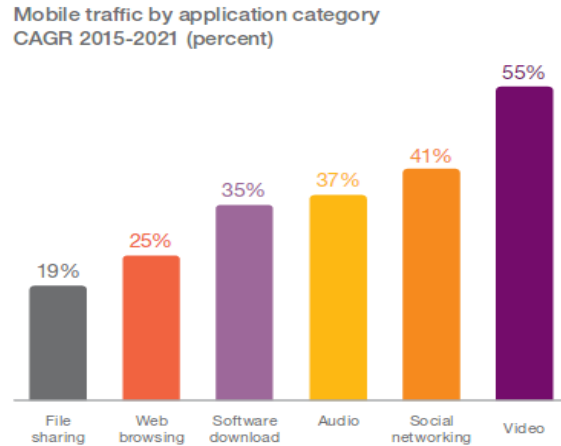


Figure 2 Traffic forecast in the future

Operators are considering a number of options to increase network capacity. These options include new techniques to improve spectral efficiency such as those being introduced in 3GPP, acquiring additional spectrum, and offload to Wi-Fi or femto cells.

A solution that the scientific community has been investigating in recent years is Licensed-Assisted Access (LAA).

The main idea of this technology is to provide operators and consumers with an additional mechanism to utilize unlicensed spectrum for improved user experience, while coexisting with other Wi-Fi and other technologies in the 5GHz unlicensed band.

3GPP conducted studies to look at the feasibility of LTE operating in unlicensed bands. A central focus of the studies was fair sharing and coexistence with Wi-Fi where the criterion used to ensure coexistence was that an LAA network does not impact existing Wi-Fi neighbors any more than another Wi-Fi network.

1.2 Task statement

In this thesis project, a new approach to communication channel has been defined which aims to improve user QoS and fairness with other technologies in the unlicensed spectrum.

The thesis is divided into three main parts: the theoretical background needed to understand the underlying idea of our algorithm and the new technologies currently in the market, a central phase where the implemented algorithm is analyzed in detail, and a final phase where the results obtained in the simulations conducted are collected and commented.

The results obtained with the algorithm developed show that it is possible to improve the

quality of the services provided to the different users by maintaining a proper sharing of the communication channel with other technologies.

The different tests conducted aim at highlighting the potentiality of the implemented algorithm and compare the performance of the currently sharing protocol (Listen-before-talk) between the nowadays technologies.

2. Technological Background

This section explains the technical background needed to understand the state of the art of new telecommunications technologies.

Detailed analysis of each single technology has permitted to define the aspects that are essential for defining a new channel sharing protocol.

2.1 Electromagnetic Spectrum

The electromagnetic (EM) spectrum is the range of all types of EM radiation. Radiation is energy that travels and spreads out as it goes – the visible light that comes from a lamp in your house and the radio waves that come from a radio station are two types of electromagnetic radiation. The other types of EM radiation that make up the electromagnetic spectrum are microwaves, infrared light, ultraviolet light, X-rays and gamma-rays.

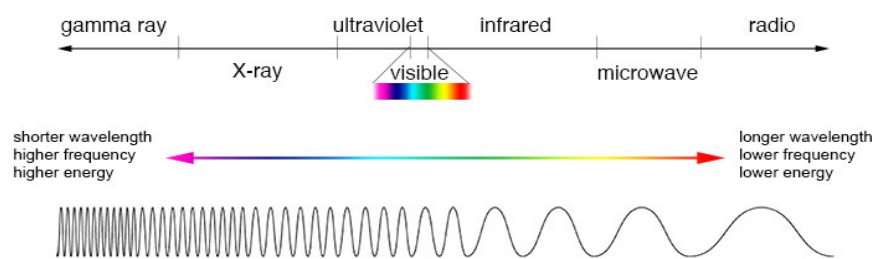


Figure 3 Electromagnetic Spectrum

Spectrum is the continuum of frequencies that characterizes radio signals.

Frequencies are measured in the number of cycles per second, Hertz, e.g., 700 MHz (700 million cycles), and spectrum is often administratively discussed in terms of bands as defined in the ITU Radio Regulation, Table of Allocations (e.g. 698– 806 MHz).

2.2 Radio Frequency Spectrum Management

Managing radio spectrum involves by and large three different processes:

1) Harmonisation: is the allocation of a frequency band for a service or set of services, at a global or regional level. It is intended to minimize interference, limit cross-border conflicts, facilitate roaming so that citizens can take equipment across borders, and to provide economies of scale for equipment manufacturers, who can manufacture equipment knowing that it will work in a number of different markets.

2) Assignment: is the process whereby an authority, such as a national regulatory agency, provides authorisation, often through an exclusive licence, to a particular organisation to use a radio frequency

band on its territory. The licence gives the organisation certainty that its signals will not be the victim of interference from other users and the incentive to invest in the infrastructure necessary to provide its service.

3)Standardisation: is the designation of technologies that will provide a certain category of service, thereby promoting economies of scale in production, ease of roaming and interoperability, as well as avoiding interference.

Radio spectrum is managed by a complex and sometimes overlapping series of international, regional and national authorities.

At the top is the International Telecommunications Union (ITU), a specialized United Nations agency with responsibility for information and communications technologies. It has the mission (among others) of ensuring equitable, efficient and economical use of the radio-frequency spectrum for all countries in the world.

The ITU allocates bands in the radio spectrum, accredits certain technologies and coordinates efforts to eliminate interference between countries, applications and terrestrial and satellite services.

2.3 Licensed vs Unlicensed Spectrum

The frequency spectrum is divided into two main branches: licensed and unlicensed.

The licensed bands are expensive and used from individual companies for exclusive use inside a given geographic area.

The main advantage of licensing is the guarantee of absence of interfere with wireless operators. The only place where interfere could take place is at the edges of the covered geographic area.

On the other side, unlicensed wireless devices operate in one of the bands set aside by the FCC (Federal Communications Commission) for industrial, scientific or medical (ISM) applications.

The unlicensed frequency bands operate usually at 2.4 GHz in most of the countries by anyone. Another commonly-used unlicensed band is the 5 GHz UNII (Unlicensed National Information Infrastructure) band.

Unlicensed wireless spectrum is free to use and the devices on it just need to respect some rules related to unlicensed band (for example, the transmission power must be 1 watt or less).

The main weakness of unlicensed frequencies is the vulnerability to interference.

2.4 From 4G to 5G

Wireless Communication is a very active area. The transformation of what has been supporting and other services leads development in areas of technology such as the data transmission, text, images, and videos.

The main telecommunications companies are constantly looking for new techniques to increase the quality of services offered over wireless networks.

Technology	1G	2/2.5G	3G	4G	5G
Deployment	1970 – 1984	1980 – 1999	1990 – 2002	2002 – 2012	2014 - now
Standards	AMPS, NMT, TACS	D-AMPS, GSM\GPRS, cdmaOne	CDMA2000\EV-DO, WCDMA\HSPA+, TD-SCDMA	LTE, LTE Advanced, VoLTE	LTE support for V2x services, LAA, eLAA,
Data bandwidth	2 Kbps	14 – 64 Kbps	2 Mbps	200 Mbps	1 Gbps and more
Services	Analog voice	Digital voice + simple data	High quality audio, video and data	Richer video content, variable devices	Dynamic information access, wearable devices with AI capabilities

table 1 Generation Technology Evolution

The exponential growth of starve connectivity cannot be fully satisfied in the coming years from 4G or from the spectrum available in the different countries. This issue is not only related to spectrum capacity, but how to use it, compress it, share and enhance it. In the near future will be essential the enhancement of an advanced management of resources and an architecture suitable for the new communication models.

In order to solve this problem, organizations such as 3GPP are contributing to the development of new communication standard known as 5G.

The principal challenges that 5G must to deal with are:

1. The expected increase of mobile subscriptions, around 8 times in the 2020.
2. The increase of applications that require higher QoS, e.g. Virtual reality, real-time devices.
3. Ensure interconnectivity between different devices and technologies, e.g. nanotechnology, cloud.
4. Set new safety standards for data security management.

2.5 Wi-Fi

Wi-Fi is a short name for Wireless Fidelity.

Wi-Fi technology has its origins in a 1985 ruling by the U.S. Federal Communications

Commission that released the bands of the radio spectrum at 900 megahertz (MHz), 2.4 gigahertz (GHz), and 5.8 GHz for unlicensed use by anyone.

This technology allows different electronic devices (such as smartphones, tablets, laptops, ...) to exchange data or connect to the internet without wires by using radio waves.

Wi-Fi Alliance is a non-profit organization that promotes Wi-Fi technology and certifies Wi-Fi products if they conform to certain standards of interoperability. The organization defines Wi-Fi devices as any "Wireless Local Area Network (WLAN) products that are based on the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards".

The principal advantage of 802.11 standard is the realization of less expensive Local Area Networks (LANs).

For the environments such as airports or outdoor areas where the interconnection of different devices without using wires is more advisable or inevitable, Wi-Fi represents the key technology.

Nowadays millions of IEEE 802.11 devices operate around the world in the same frequency bands, compromising the coexistence between them. Some consumers and businesses still using old standards for years (e.g. 802.11b), because they use type of devices that meet their needs and there are not need to changes.

One of the most challenging problem that 802.11 evolution needs to deal with is therefore the “play fair” with the older standards.

2.5.1 IEEE 802 Standard Structure

IEEE 802.11 standard belongs to the family of IEEE 802 standards that include Local Area Network standards and Metropolitan Area Network standards.

The IEEE 802 family of standards is supported by the IEEE 802 LAN/MAN Standards Committee (LMSC).

IEEE 802.11 specifications include physical layer (PHY) and medium access control (MAC) and offer services to a common 802.2 logical link layer (LLC) for implementing Wireless Local Area Network (WLAN) communication.

The 802.11 family is a series of over-the-air modulation techniques that share the same basic protocol (table below).

IEEE 802 Standards	
802.1	Bridging & Management
802.2	Logical Link Control
802.3	Ethernet – CSMA/CD Access Method
802.4	Token Passing Bus Access Method
802.5	Token Ring Access Method
802.6	Distributed Queue Dual Bus Access Method
802.7	Broadband LAN
802.8	Fiber Optic
802.9	Integrated Services LAN
802.10	Security
802.11	Wireless LAN
802.12	Demand Priority Access
802.14	Medium Access Control
802.15	Wireless Personal Area Networks
802.16	Broadband Wireless Metro Area Networks
802.17	Resilient Packet Ring

table 2 802 evolution

The specifications of each standards provide the basis for wireless network products using the Wi-Fi brand.

2.5.2 IEEE 802.11 Phy Standards

The following table represents an overview of the evolution of the principals 802.11 physical layer standards:

Standards	Release Date	Operating frequencies	Bandwidth (MHz)	Modulation	Advanced Antenna technologies	Maximum Data Rate
802.11	1997	2.4 GHz	20 MHz	DSSS, FHSS	N/A	2 Mbits/s
802.11b	1999	2.4 GHz	20 MHz	DSSS	N/A	11 Mbits/s
802.11a	1999	5 GHz	20 MHz	OFDM	N/A	54 Mbits/s
802.11g	2003	2.4 GHz	20 MHz	DSSS, OFDM	N/A	542 Mbits/s
802.11n	2009	2.4 GHz, 5 GHz	20 MHz, 40 MHz	OFDM	MIMO, up to 4 spatial streams	600 Mbits/s
802.11ac	2013	5 GHz	40 MHz, 80 MHz, 160 MHz	OFDM	MIMO, MU-MIMO, up to 8 spatial streams	6.93 Gbits/s

Table 3 802.11 Phy Evolution

As we can see the creation of new modulation schemes and antenna structures are the main responsible for the exponentially growth of the data rate performance during the years.

In order to understand the implementation choices of our research, the following table presents the advantages and disadvantages of each previous standards.

Standards	Advantages	Disadvantages
802.11	/	Slow network bandwidth for most applications
802.11b	Slowest and least expensive existing standard	Interference issues with other products operating in the 2.4 GHz band
802.11a	-Less signal degradation the ISM band -OFDM has high performance in a high multipath	Operational range slight less than previous standard
802.11g	-high speed, reduced costs -hardware compatible with 802.11b	Interfere problem as 802.11b
802.11n	Improve WLAN range, reliability, throughput	At 2.4 GHz interfere problem as 802.11b
802.11ac	-backwards compatibility and coexistence with some of previous standards -interconnectivity between different devices	Short range distance penetration

table 4 802.11 Evolution: Pros and Cons

2.5.3 Protocol Architecture

The OSI model is a layered model that describes how information moves from an application program running on one networked computer to an application program running on another networked computer.

The standard 802.11 deals with the two lowest layers of OSI, the physical and data link layer (or Media Access Control layer).

These two last layers, illustrated in detail in the following image, are the only difference between the different types of 802.11 standards.

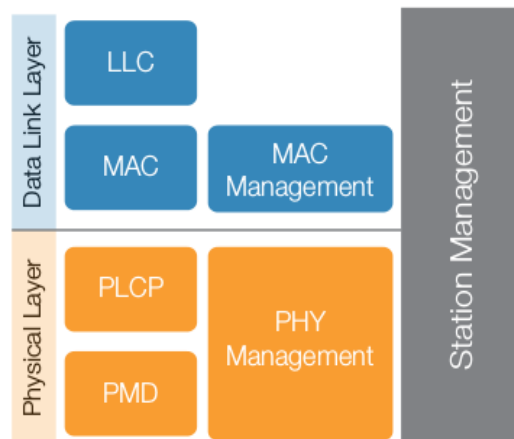


Figure 4 Layer 1 and 2

The role of MAC layer is to provide all the services necessary for transfer data between different network parts, correct errors that occurs at physical layer.

The different tasks at MAC layer are divided into MAC sub-layer and MAC management sub-layer. The first sub-layer defines packet formats and access mechanism, the latter defines power management, security and roaming services.

At lowest level, Physical Layer defines electrical and physical specifications for devices, defining the setting between a transmission medium and a device.

As we can see from figure 4, the Physical Layer has 3 sub-layers:

1. Physical Layer Convergence Procedure (PLCP): it minimizes the dependence of the MAC layer on the PMD sublayer by mapping MPDUs into a frame format suitable for transmission by the PMD. It also manages the frame transmission between wireless medium and MAC layer.
2. PHY Management: take care of management issues like channel tuning.
3. Physical Medium Dependent (PMD): provides transmission and reception of Physical layer data units between two stations via the wireless medium. In order to deliver this service, the PMD interfaces with the wireless air channel and provides modulation / demodulation of the frame transmissions.

We can summarize the principal functions of physical layer in the following list:

- start and terminate connection on the medium
- resource sharing between multiple users
- conversion/modulation of data from digital to analog systems

2.5.4 MAC layer protocol

The modeling of the 802.11 MAC layer is an important issue for the evolution of this technology.

The 802.11 standard have been defined two mechanisms at this layer: Distributed Coordination Function (DCF) and Point Coordination Function (PCF).

The DCF mechanism employs Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for define how share the channel among stations.

The PCF is defined as an option to help time-bounded delivery of data frames.

There are two access methods for DCF protocol: a basic access method and request-to-send / clear-to-send (RTS/CTS) method.

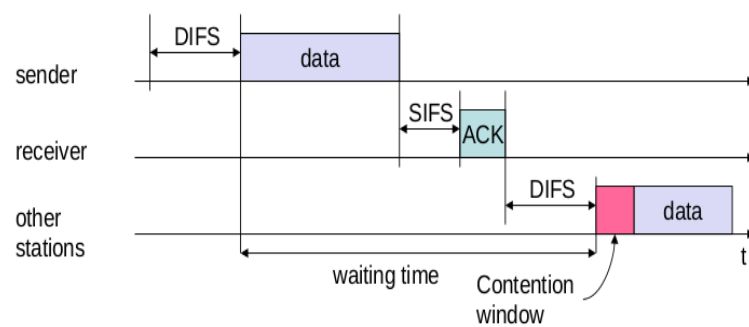


Figure 5 Basic Access Scheme

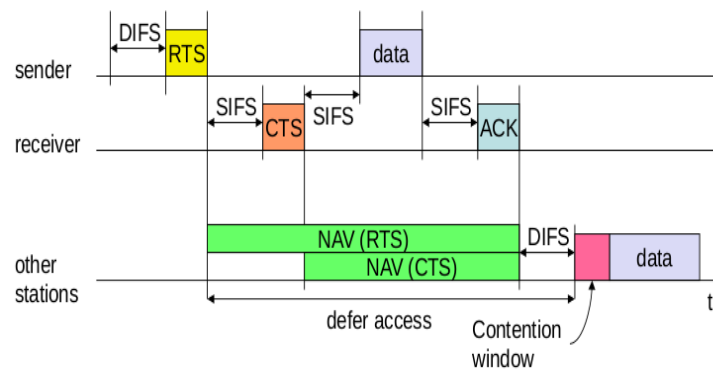


Figure 6 RTS/CTS mechanism

If the channel is sensed busy from the source STA, a backoff time, measured in slot times, is selected randomly between $[0, CW)$, where CW represents the contention window.

This backoff timer is decremented by one as long as the channel is sensed idle for a DIFS (Distributed Inter Frame Space) time. In case the medium is busy, the timer is not decremented until it is not sensed idle again.

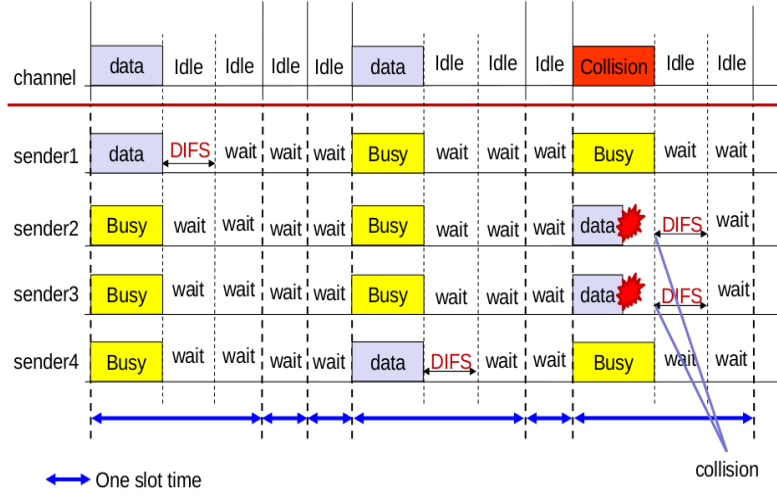


Figure 7 Collision Stations Status

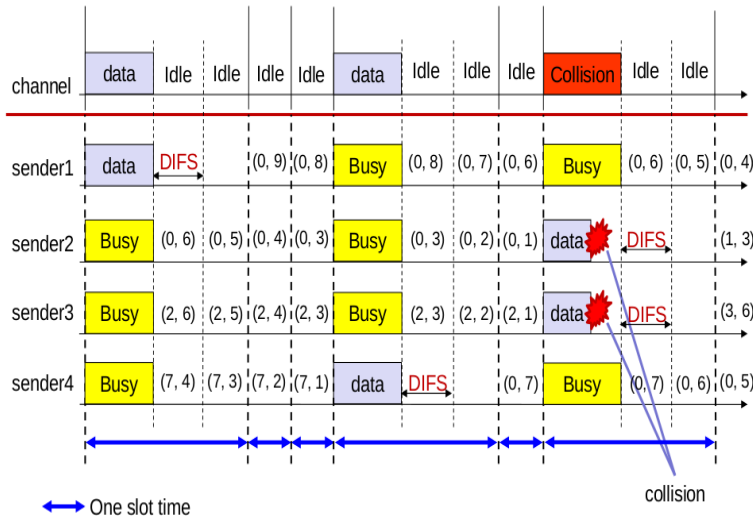


Figure 8 Stations states: (backoff stage, backoff timer)

The size of the CW parameter is defined by the PHY layer expressions: CW_{min} and CW_{max} .

Every time a transmission failed, the value of CW is doubled up to the maximum value $CW_{max} + 1$.

When the backoff timer reaches zero, the station is ready to transmit the data packet. In order to apply the Collision Avoidance scheme, the station generates a random backoff interval before transmitting to minimize the probability of collision with packets being transmitted by other stations.

In order that the transmission is successfully ended, the receiver must send ACK frame after a SIFS (Short Inter Frame Space) time, which is less than DIFS (DCF Interframe Space), otherwise another station could detect the channel as free and start to transmit.

The ACK frame is also necessary because the CSMA/CA mechanism doesn't rely on the capability of the stations to detect a collision by hearing their own transmission.

If the station doesn't receive the ACK frame within a specified ACK timeout or another transmission of a different packet is detected, it reschedules the packet transmission

according to the given backoff rules.

In addition, to avoid channel capture, a station is forced to wait a random backoff time between two consecutive new packet transmissions, even if it has all the rights to transmit again.

Meanwhile a station transmits, all the other stations configure their Network Allocation Vector (NAV) which limits the need for physical carrier-sensing at the air interface in order to save power.

The above description is a two-way handshaking technique for the packet transmission called basic access mechanism.

The basic access mechanism achieves good performances for small size data frame packets, but suffers from the hidden terminal problem, that occurs when a node is visible from a wireless access point (AP) but not from other nodes communicating with that AP. This issue can be solved with RTS/CTS mechanism, where the transmission of data packet and its corresponding ACK can proceed without interference from other nodes.

In this mechanism, a station that wants to transmit applies the same procedure as the basic access mechanism, but, before transmitting data packet, sends a special short frame called request to send (RTS).

When the receiving station detects the RTS frame, it waits a SIFS time and responds with a clear to send (CTS) frame. The transmission occurs only if the CTS frame is correctly received.

The frames RTS and CTS carry the length information of the packet to be transmitted. Thanks to this information, all the stations are able to update the NAV vector with the time that the channel will be busy.

2.5.5 PHY layer protocol

In table 3 are described the main characteristics of the most important IEEE 802.11 physical layer standards.

This layer uses two types of transmission modes: burst or packets.

The packets are divided into three functions: Management Frames, Control Frames and Data Frames.

Each packet contains a Preamble, Header and Payload data.

The 802.11 PHY standards support different rates for packet transmission; the PLCP header is sent at the basic rate (1 Mbps), while the rest of the packet might be sent at a higher rate.

The Preamble contains information regarding synchronization and channel characteristics for equalization, the Header provides information about packet setting (format, data rate,...), and the Payload Data contains the user data.

This layer transmits ACK, RTS, CTS and PLCP header with basic transmission mode which has the maximum coverage range for all transmission modes.

The maximum range is obtained with efficient modulation schemes like BPSK and DBPSK, which have low bit error probability for a given SNR.

Figure 9 shows the general packet structure for 802.11 standards.

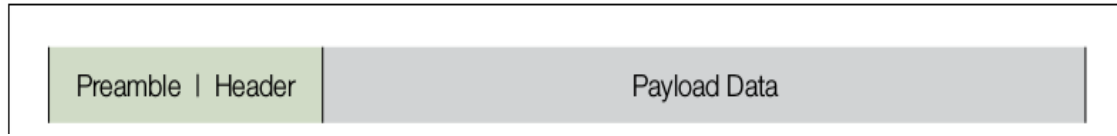


Figure 9 Frame Structure

2.5.6 Performance Analysis

This section gives a detailed overview of the major parameters utilized for performance evaluation following the Bianchi's model.

The model assumes a two steps analysis: first, it obtains the stationary probability r that a station transmits a packet in a random chosen slot time, then calculate the throughput as function of r .

All the parameters must to be evaluated in saturation condition, which means that the system works all the time at maximum load (the queue of each station is assumed to be always nonempty).

Moreover, we assume ideal channel conditions (no hidden terminals, no capture effect).

2.5.7 Packet Transmission Probability

According with saturation condition, each packet needs to wait a random backoff time before being transmitted.

We define $b(t)$ as the stochastic process representing the backoff timer at time t and $s(t)$ the backoff stage $(0, m)$ of the station at time t .

The key approximation in this model is that each packet collides with constant and independent probability p , without considering the number of retransmissions happened.

We define p as the *conditional collision probability*, meaning that this is the probability of a collision seen by a packet being transmitted on the channel.

Once independence is assumed and p is supposed constant, the bi dimensional process $\{s(t), b(t)\}$ can be modeled with discrete-time Markov chain, as showed in figure 10.

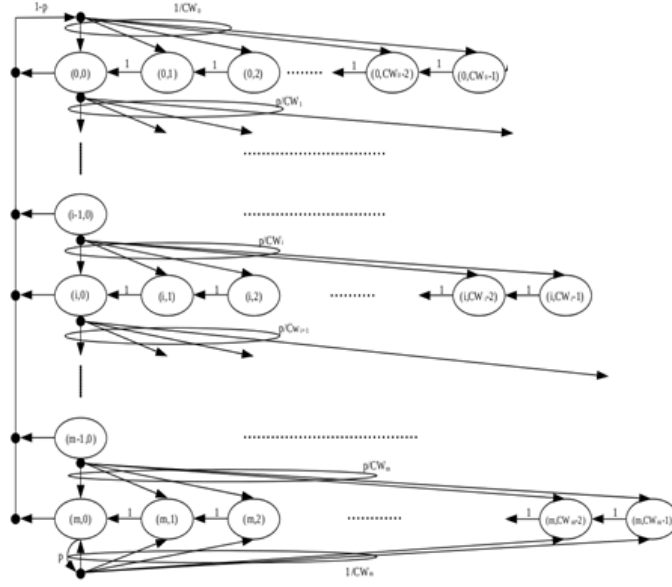


Figure 10 Markov backoff process

The transition probabilities between the different steps can be described with the following notation:

- $P\{s(t+1)=i, b(t+1)=k \mid s(t)=i, b(t)=k+1\} = 1 \quad k \in (0, CW_i-2), i \in (0, m) \rightarrow$ with probability 1 the backoff time is decremented at the beginning of each slot time.
- $P\{s(t+1)=0, b(t+1)=k \mid s(t)=i, b(t)=0\} = (1-p)/CW_0 \quad k \in (0, CW_0-1), i \in (0, m) \rightarrow$ after a successfully packet transmissions, the backoff time restarts from stage 0, uniformly chosen in the $0 - CW_0-1$ range.
- $P\{s(t+1)=i, b(t+1)=k \mid s(t)=i-1, b(t)=0\} = p/CW_i \quad k \in (0, CW_i-1), i \in (1, m) \rightarrow$ in case of unsuccessfully transmission, the backoff stage increases and its value is chosen in the range $0 - W_i$.
- $P\{s(t+1)=m, b(t+1)=k \mid s(t)=m, b(t)=0\} = p/CW_m \quad k \in (0, CW_m-1) \rightarrow$ in case of unsuccessfully transmission in stage m , is not possible to increase the backoff stage.

Once we have all the transition probabilities, is possible to define the stationary distribution of the chain:

$$b_{i,k} = \lim_{t \rightarrow \infty} P\{s(t)=i, b(t)=k\}, i \in (0, m), k \in (0, CW_i-1)$$

Starting from basic statistic knowledge that sum of all probabilities must to be equal to 1, we can express the backoff time in relation with conditional collision probability in order to obtain the probability r (function of p) that a station transmits in a randomly chosen slot time as:

$$r(p) = \frac{2}{1+W+p \cdot W \cdot \sum_0^{m-1} (2p)^i}$$

This function is monotone decreasing function, starting from $r(0) = 2 / (W+1)$ and reduces up to $r(1) = 2 / (1+2^m W)$.

2.5.8 Throughput

Bianchi's paper defines the normalized system throughput S as the fraction of time the channel is used to successfully transmit the payload bits.

$$S = \frac{\text{average transmitted payload bits for slot time}}{\text{average slot time dimension}}$$

To compute S , we need to define the following probabilities:

- $P_{tr} = \frac{1-(1-r)^n}{1}$ probability of at least one transmission in considered slot time.
- $P_s = \frac{n \cdot r \cdot (1-r)^{n-1}}{1-(1-r)^n}$ probability that a transmission occurring on the channel

Defined $E[P]$ the average packet payload size, T_s the average time that the channel is sensed busy, and T_c the average time the channel is sensed busy by each station for a collision, is possible to express the throughput S as:

$$S = \frac{P_s \cdot P_{tr} \cdot E[P]}{(1-P_{tr}) \cdot \sigma + P_{tr} \cdot P_s \cdot T_s + P_{tr} \cdot (1-P_s) \cdot T_c}$$

The numerator represents the average amount of payload information successfully transmitted in a slot time, since a successful transmission occurs in a slot with probability $P_s P_{tr}$.

The denominator is the combination of three terms: probability $(1-P_{tr})$ that the slot is empty, the probability $(P_s P_{tr})$ of success transmission, and the probability $P_{tr}(1-P_s)$ that the slots contains a collision.

The type of access mechanism employed during throughput calculation is regulated by the parameters T_s and T_c .

For basic access mode, the two previous parameters assume the following expressions:

- $T_s^{\text{bas}} = \text{PHY}_{\text{hdr}} + \text{MAC}_{\text{hdr}} + E[P] + \text{SIFS} + \delta + \text{ACK} + \text{DIFS} + \delta$
- $T_c^{\text{bas}} = \text{PHY}_{\text{hdr}} + \text{MAC}_{\text{hdr}} + E[P^*] + \text{DIFS} + \delta$
- and for RTS/CTS mechanism:
- $T_s^{\text{rts}} = \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta + \text{PHY}_{\text{hdr}} + \text{MAC}_{\text{hdr}} + E[P] + \text{SIFS} + \delta + \text{ACK} + \text{DIFS} + \delta$
- $T_c^{\text{rts}} = \text{RTS} + \text{DIFS} + \delta$

Where δ is the propagation delay and $E[P^*]$ is the average length of the longest packet payload involved in a collision. In our case, all the packets have the same size, so $E[P^*] = E[P]$.

This analytical model is particularly efficient for evaluate the maximum saturation throughput.

For his model, Bianchi fixed as constants $T_s, T_c, E[P], \sigma$ and maximizes throughput formula obtaining the following expression:

$$\frac{E[P]}{T_s - T_c + (\sigma * \frac{1 - P_{tr}}{P_{tr}} + T_c)/P_s}$$

Maximizing this expression is possible if we maximize the non-constant part of the denominator respect to r :

$$\frac{P_s}{\left(\frac{1 - P_{tr}}{P_{tr}}\right) + T_c/\sigma} = \frac{n * r * (1 - r)^{(n-1)}}{T_c' + (1 - r)^n * (T_c' - 1)}$$

$$(1 - r)^n - T_c' \{n r - [1 - (1 - r)^n]\} = 0$$

$$r \approx \frac{1}{n * \sqrt{\left(\frac{T_c'}{2}\right)}}$$

The maximum performance depends from transmission probability r . Because of the number of stations n is difficult to control in the environment, we can only set the system parameters m and W for the best performance based on the estimated value of n .

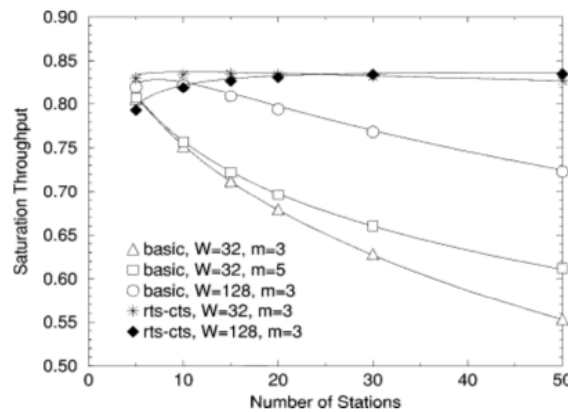


Figure 11 Bianchi's throughput

2.6 LTE

LTE is a standard for high-speed wireless communication developed for satisfy the growing mobile broadband market.

This technology belongs to the transition from 3G to 4G technologies and the first version was presented in release 8 of 3GPP.

Thanks to this new technology, the user experience is further enhanced for meet demand of new applications as interactive TV, streaming video, advanced games or professional services.

The main benefits for users and operators are:

1. Simplicity: LTE supports different bandwidth sizes, from 1.4 to 20 MHz, and both frequency division duplex (FDD) and time division duplex (TDD). Moreover, new bands are discovered from 3GPP. This means that operators can implement and manage this technology with more flexibility and easier implementation.
2. Capacity and Performance: LTE provides higher downlink (> 100 Mbps) and uplink (> 50 Mbps) peak rates.
3. Wide range of terminals: operator can introduce the flexibly to match existing network and devices for mobile broadband and multimedia services.
4. Costs: Reduced CAPEX and OPEX including backhaul shall be achieved. Cost effective migration from 3GPP Release 6 UTRA radio interface and architecture shall be possible.
5. Mobility: lte optimizes communication for low mobile speed (0 – 15 km/h), but also higher speeds (e.g. trains) must to be supported.
6. QoS: new services with higher quality are possible with LTE.

2.6.1 Evolution

One of the important feature of LTE is the reduced complexity architecture. Figure 12 compares architecture of GSM, GPRS, UMTS with LTE.

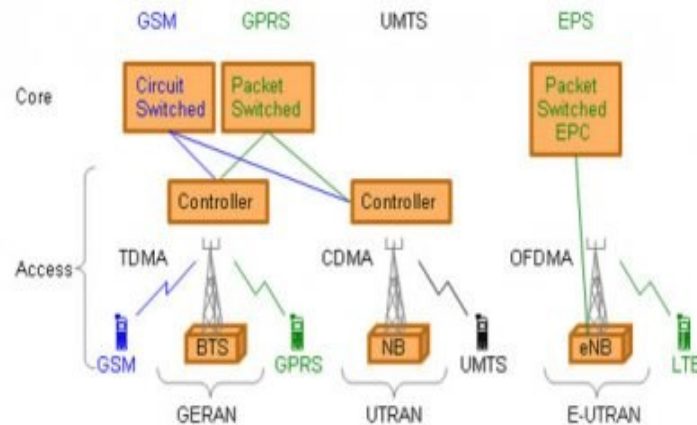


Figure 12 GSM, GPRS, UMTS and LTE architecture

The blue part inside the figure represents the GSM architecture, which was developed for carry real-time and data services on a circuit switched technology.

The low data rates achieved with circuit switched forced 3GPP to study new architecture based on IP packed switching (green lines).

This solution has contributed to the evolution of GPRS, with the same air interface and access method of GSM, the TDMA (time division multiple access).

To reach high data rates with UMTS (Universal Mobile Terrestrial System) technology, was developed a new access technology, WCDMA (Wideband Code Division Multiple Access).

The access network in UMTS emulates a circuit switched connection for real time services and a packet switched connection for data services (black in figure 12).

UMTS allocates the IP address to the user device when it requires a service; the IP will be released when the service is ended.

The Evolved Packet System (EPS) is purely IP based. Both real time and data services will be carried by the IP protocol. The IP address is allocated when the mobile is switched on and released when switched off.

2.6.2 Architecture

In order to guarantee different QoS to the user, EPS provides multiple bearers to different PDN (Packet Data Network). For example, a user can perform web browsing at the same time of voice call (VoIP).

Based on the type of traffic to forward, exist different kind of bearers. Moreover, the

network must provide privacy, security and protection against fraudulent use to the users. This is possible using different EPS (Evolved Packet System) elements with different roles.

Figure 13 shows the overall network architecture, including standardized interfaces and network elements.

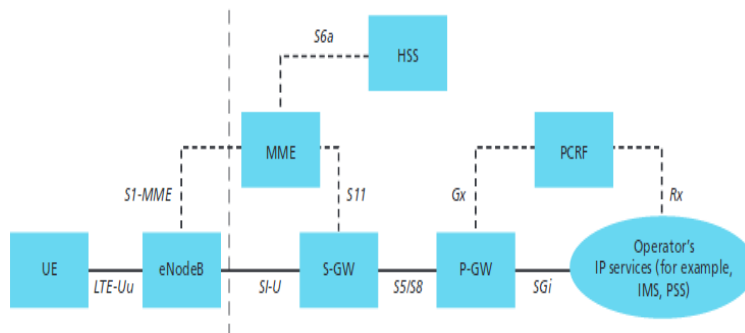


Figure 13 Network Architecture

From a high level overview, the network is formed by the Core Network (EPC) and the Access Network E-UTRAN.

The access network is constituted from the evolved NodeB (eNodeB) and the connected user equipment (UEs). On the other side, the core network consists of many logical nodes. All the networks elements are interconnected through interfaces that are standardized in order to allow vendors interoperability.

Thanks to this sub-division of interfaces, network operators may choose to split or merge these logical network elements in their physical implementation, based on commercial considerations.

More detail overview of the EPC and E-UTRAN is described in the following picture.

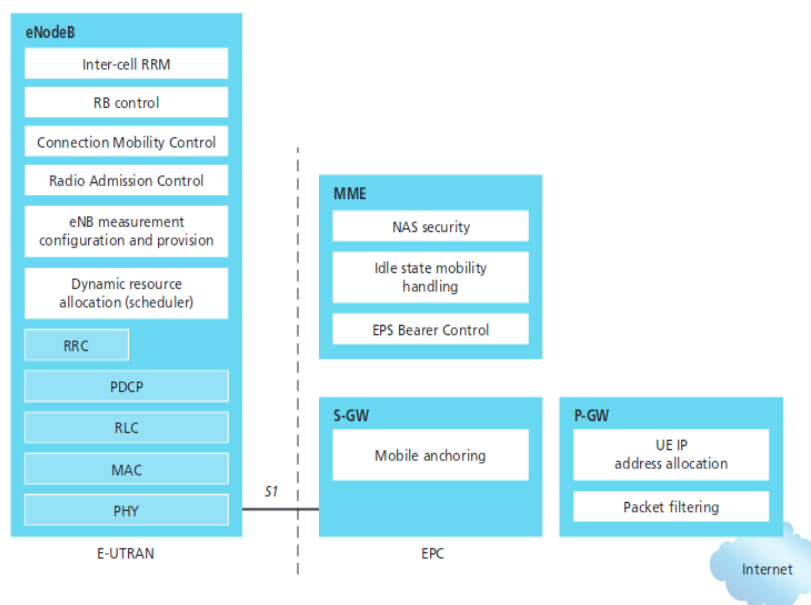


Figure 14 EPC and E-UTRAN architecture

2.6.3 Core Network

The core network (EPC) is responsible for the global control of the UEs and connection of the bearers.

The main nodes of the EPC are:

1. PDN Gateway (P-GW): is responsible for IP address allocation for the UE, QoS enforcement and flow charging according to rules of PCRF. This interface, based on Traffic Flow Templates (TFTs), can perform filtering of downlink user IP packets into the different QoS-based bearers.

Another important role of P-GW is to be the mobility anchor for interworking with non-3GPP technologies such as WiMAX and CDMA2000 networks.

2. Serving Gateway (S-GW): it serves as the local mobility anchor for the data bearers when the UE moves between eNodeBs. This interface also performs some administrative functions such as collecting information about load and lawful interception in the visited network.

Moreover, it works as a bridge for internetworking between other 3GPP technologies such as packet radio service (GPRS) and UMTS.

3. Mobility Management Entity (MME): manages the signaling between the UE and CN. This interface supports two main functions: bearer management (that includes establishment, maintenance and release of the bearers) and connection management (manage connection and security between the network and the UE).

Other secondary nodes are:

1. Home Subscriber Server (HSS): contains users' SAE (System Architecture Evolution) subscription (e.g. EPS-subscribed QoS profile, roaming restrictions). This interface also collects information about the connection between PDN and UE. This is performed with two methods: access point name (APN) or PDN address.

The HSS may also manage the authentication center (AUC), which is responsible for authentication and security keys.

2. Policy Control and Charging Rules Function (PCRF): there are two main roles: decision-making and flow-based charging control. The PCRF gives the QoS authorization that decides how to manage a specific data flow and check that it agrees with user's subscription profile.

3. IP Multimedia Subsystem (IMS): is an architectural framework for delivering Internet Protocol (IP) multimedia services.

2.6.4 Radio Resource Control (RRC)

The role of layer 3 implemented in LTE is to manage the following procedures over the air interface:

- Configuration control measurements.
- Quality of Service (QoS) control.
- Mobility Control.
- RRC connection configurations (paging, establishing/configuring/releasing RRC connections, define identities for UEs).
- System Information Broadcasting.

RRC layer plays the fundamental role inside LTE standard of guarantee seamless service continuity between different technologies as GSM/GPRS, WCDMA/HSPA and CDMA2000.

The handovers schemes for support mobility between different technologies are showed in figures 15 and 16.

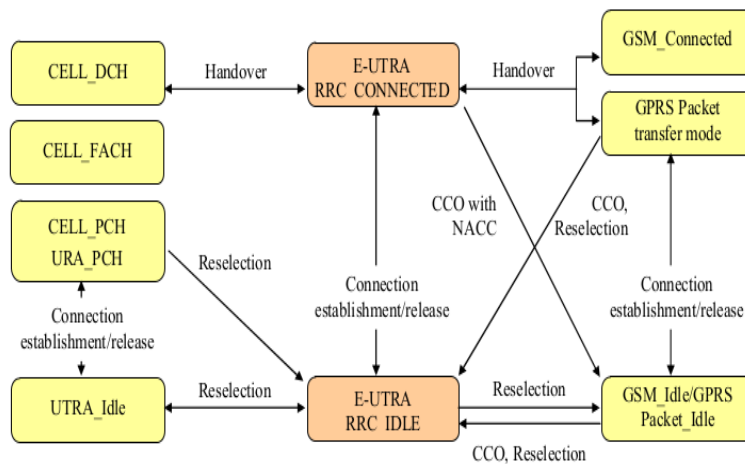


Figure 15 Mobility Scheme for Different Technologies

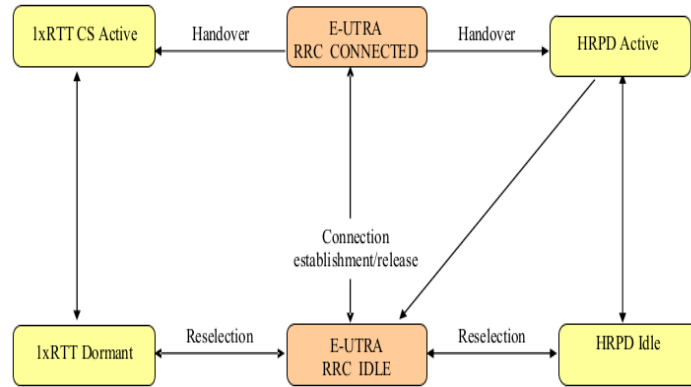


Figure 16 Handovers Overview

The following list shows the parameters that can be configured in the lower layer of RRC. The advantage of this cross-layer configuration is the easier PHY layer parameterization for specific applications and scenarios.

- PDSH: reference signal configuration
- PHICH: short-long duration configuration, setting of PHICH group
- MIMO: transmission mode
- CQI reporting: PUCCH resource, format and periodicity
- Scheduling request: resource and periodicity
- PUSCH: hopping mode, available sub-bands, ACK/NACK power setting, CQI
- PUCCH: available resources, enable\disable simultaneous transmission of ACK/NACK and CQI
- PRACH: preambles configuration, starting power, response window size, maximum number of contention resolution timer
- Uplink demodulation reference signal: group assignment (group hopping, group sequence hopping)
- Uplink sounding reference signal: bandwidth and subframe configuration, duration, periodicity, hopping information, simultaneous transmission
- Uplink power control: UE special power setting parameters, size for PUCCH and PUSCH
- TDD-specific parameters: DL/UL subframe configuration

2.6.5 LTE PHY and MAC layers

The LTE physical layer can support full duplex communication on the channel. It operates continuously for downlink with sync functions in order to provide multiple channels at the same time by varying the modulation setting.

LTE introduces the concept of Resource Block, that consists in a block of 12 subcarriers in one slot. A group of resource blocks with the same modulation/coding scheme is called Transport Block (TB).

A transport block contains the data allocated for a specific UE during a precise period. The well-structured LTE physical layer permits to serve multiple UEs in downlink in one transport block at any time.

Figure 17 and 18 show the downlink and uplink architecture of MAC layer. The PHY layer communicates with the MAC layer through transport channels. The MAC layer and the RLC layer communicate with logical channels.

On the top of PDCP layer, the standard provides radio bearers to carry signaling and user data.

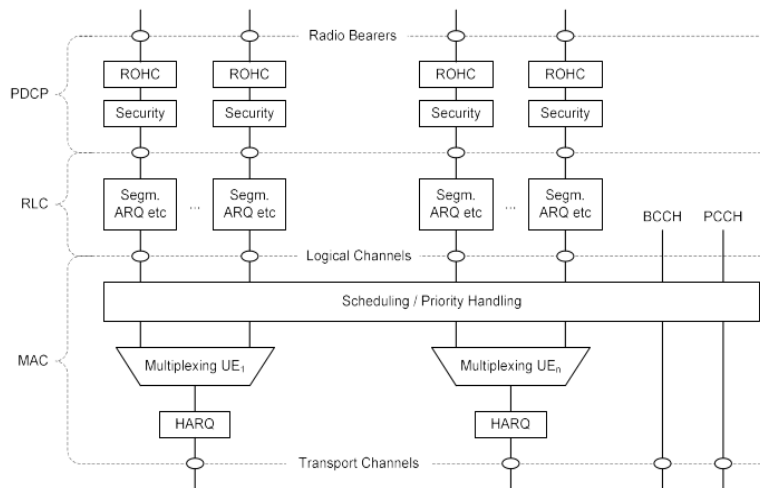


Figure 17 Downlink Architecture

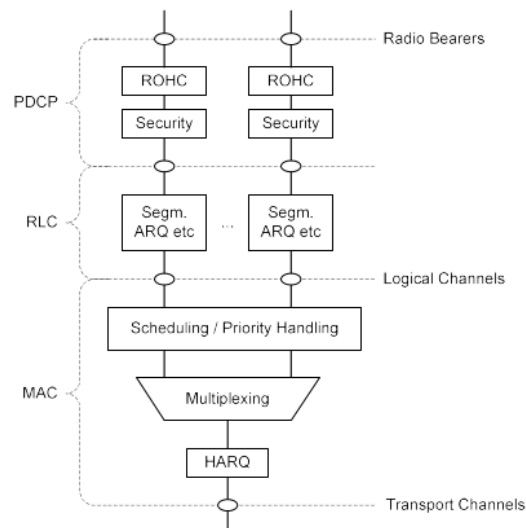


Figure 18 Uplink Architecture

The LTE standard specifies the following physical channels:

- Physical broadcast channel (PBCH): it maps the transport block to four subframes separated from 40 ms of interval. Under good channel conditions each subframe can be decoded independently.
- Physical control format indicator channel (PCFICH): this field is transmitted in every subframe and contains information about the number of OFDM symbols are used for the PDCCHs.
- Physical downlink control channel (PDCCH): send to the UE the resource allocation of paging channel (PCH), downlink shared channel (DL-SCH) and its Hybrid ARQ information.
- Physical Hybrid ARQ Indicator Channel (PHICH): carries ACK/NAK responses to the uplink transmissions.
- Physical downlink shared channel (PDSCH): carries PCH and DL-SCH
- Physical multicast channel (PMCH): carries multicast channel (MCH)
- Physical uplink control channel (PUCCH): carries CQI reports, Scheduling request and ACK/NAKs in response to downlink channel.
- Physical uplink shared channel (PUSCH): forwards the UL-SCH
- Physical random access channel (PRACH): carries the random access preamble

2.6.6 LTE Downlink Scheme

LTE downlink transmission scheme, for both FDD and TDD modes is based on OFDM, is showed in figure 19(for a 5 MHz signal bandwidth).

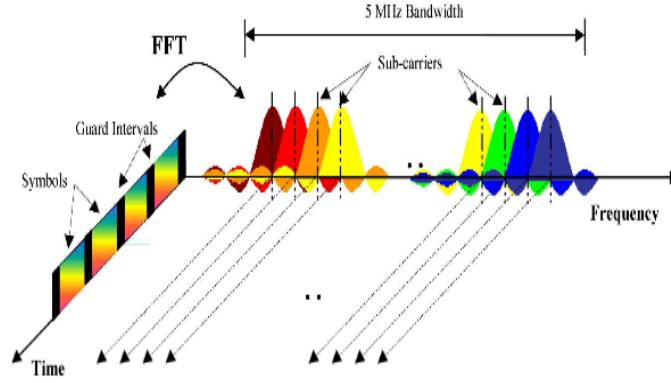


Figure 19 LTE Downlink Overview

This modulation divides the spectrum into subcarriers, each one modulated independently by a low rate data stream.

To modulate and transmit data symbols, E-UTRA utilizes QPSK, 16QAM and 64 QAM downlink modulation schemes.

Between two consecutive symbols, in the time domain is added a guard interval. The value of this parameter depends from the environment (e.g. indoor, rural, city center) and is important to solve inter-symbol-interference (ISI) due to channels delay spread.

From practical point of view, the OFDM signal can be generated using IFFT (Inverse Fast Fourier Transform) digital signal processing. This technique converts a number N of data symbols used as frequency domain bins into the time domain signal.

Figure 20 shows the symbol generation procedure.

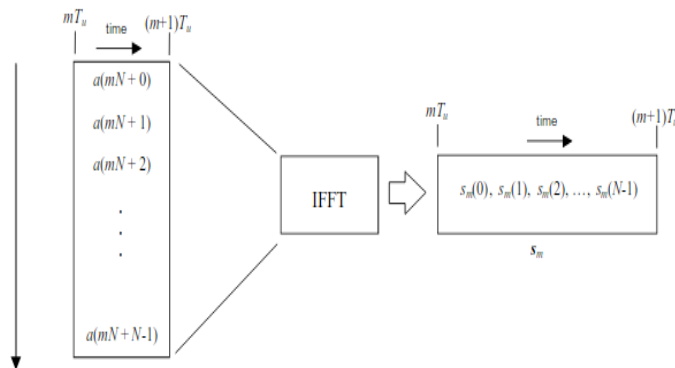


Figure 20 Symbol Generation

The N parallel orthogonal subcarriers, each one independent and with sinc function shape, are elaborated from IFFT block, which generates the OFDM symbol s_m .

Downlink data transmission

In the frequency domain, 12 subcarriers constitute one Resource Block(RB). A RB occupies a bandwidth of 180 kHz, with a spacing of 15 kHz between the subcarriers.

The number of RB depends from the channel bandwidth employed.

Data are allocated in terms of multiple RB to a device (UE) in the frequency domain. In the time domain, the scheduling policy can be modified every transmission time interval of 1 ms; this decision is taken from the base station (eNodeB).

In order to allocate in efficient way the RBs, the scheduling algorithm must to take into account different factors: radio link quality, interference situation of the scenario, QoS required, service priorities, etc.

The user data is carried on the Physical Downlink Shared Channel (PDSCH). The PDSCH is the only channel that can be modulated with QPSK, 16QAM or 64QAM.

Figure 22 is an example of allocation downlink for 6 users.

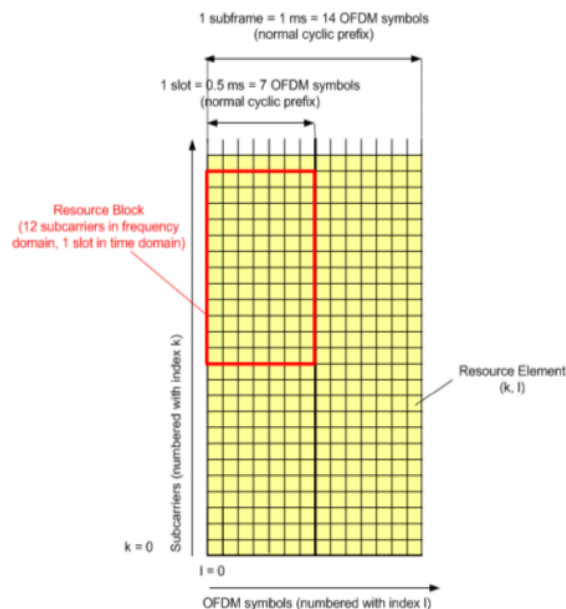


Figure 21 Resource Block Structure

2.6.7 LTE Uplink Scheme

The OFDMA modulation scheme for the Downlink mode is not employed in Uplink mode due to the weak peak-to-average power ratio (PAPR) properties of an OFDMA signal. For both TDD and FDD modes, LTE Uplink utilizes SC-FDMA (Single Carrier Frequency Division Multiple Access) modulation scheme, with cyclic prefix. The main reason of this choice is the better PAPR properties obtained with SC-FDMA compared to an OFDMA signal. Moreover, this property guarantees less cost-effective design of the power amplifiers on the UE.

The implementation of SC-FDMA for E-UTRA is realized with DFT-spread-OFDM (DFT-s-OFDM) transmission scheme.

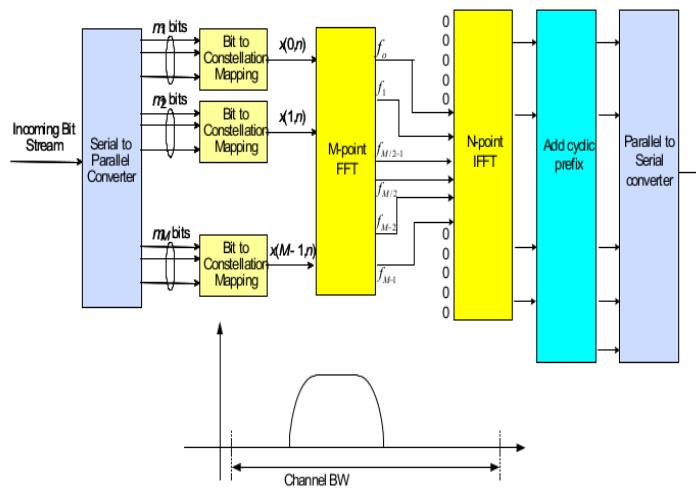


Figure 24 Block Diagram DFT OFDM

Figure 24 shows the Block diagram of a DFT OFDM scheme. The structure starts with a M DFT blocks as input of FFT M-point block. The type of mappings of the M blocks supported by Uplink scheme are QPSK, 16QAM and 64QAM.

The M-point FFT processes the M input signal and gives as output M subcarriers.

The last steps consist in a N-point IFFT ($N > M$) as in OFDM followed by a cyclic prefix and parallel to serial conversion blocks.

The main difference between OFDMA and SC-FDMA is the DFT processing. With this type of processing, each subcarrier contains information of all transmitted modulation symbols, because the input data stream has been spread over all the subcarriers from the DFT transforms. In contrast, OFDMA subcarriers contain only information of specific modulation symbols.

Uplink data transmission

The scheduling operations of uplink are operated by eNodeB, which assigns time/frequency resources to the UEs and inform them about transmission parameters.

How is computed the scheduling depends from QoS parameters, UE queue, uplink channel quality, UE performances, etc.

In uplink, data are allocated in multiples of one resource block, which has size of 12 subcarriers in the frequency domain as the downlink scheme. However, for simplify the DTF design, in uplink not all the integer multiples are allowed. Figure 25 shows a possible allocation RB scheme.

1	2	3	4	5	6	8	9	10	12
15	16	18	20	24	25	27	30	32	36
40	45	48	50	54	60	64	72	75	80
81	90	96	100						

Figure 25 Uplink Allocation RB Scheme Example

Figure 26 shows slot structure for uplink transmission.

Each slot is formed by 7 SC-FDMA symbols when normal cyclic prefix is enable, otherwise 6 SC-FDMA in case of extended cyclic prefix configuration. The symbol number 3 carries the demodulation reference signal (DMRS) that is necessary for correct demodulation at eNodeB side and channel quality evaluation.

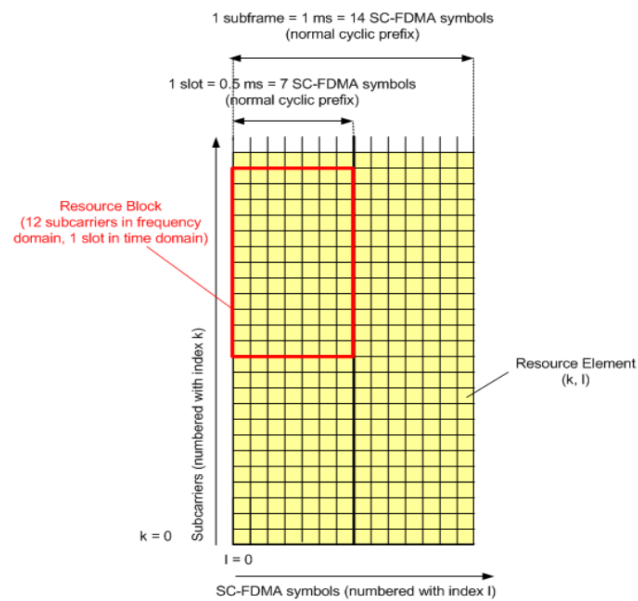


Figure 26 Uplink Slot Structure

As mentioned above, uplink and downlink processing are similar. Other key differences are the peak data rate that is half in uplink than downlink, changes in logical, transport channels and in the random access for initial transmissions.

Random Access Procedure (RACH)

RACH mechanism is used in four cases:

1. Handover requires random access procedures.
2. UL data arrives when are not scheduling request available.
3. Radio failure or access from disconnected state.
4. DL or UL data arrival after UL PHY has lost synchronization.

The mobility of UE from a base station requires perfect timing operations since the delay can involve collisions or timing synchronization problems.

The LTE uplink standard implements two forms of RACH: contention-based and non-contention based.

Contention-based Random Access

This type of random access can be applied to all the four cases listed before. It works on a 4 steps procedure.

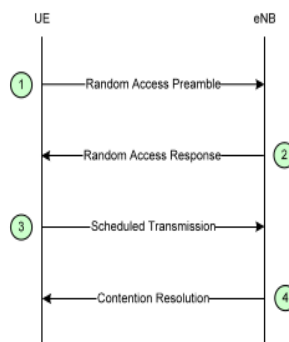


Figure 27 Four Steps Procedure

1. Random access preamble: send to the physical layer a resource with the subcarriers allocated for this purpose.
2. Random access response:
 - Sent by physical downlink control channel (PDCCH) within a time window of a few TTl.
 - During the first access is exchanged RA-preamble identifier, timing synchronization information, initial UL grant, etc.
 - More than one UE can fit one response.
3. Scheduled transmission:
 - Employs HARQ and RLC on UL SCH.

- Communicate UE identifier.

4. Contention resolution: the eNodeB can use this step to end up the RACH procedure.

Non-Contention-based Random Access

This technique can be applied to only handover and DL data arrival.

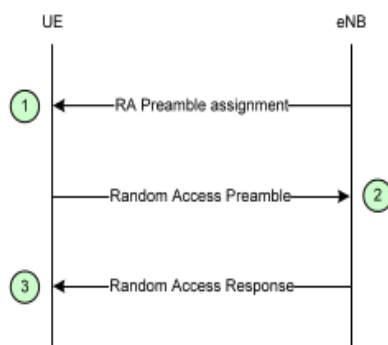


Figure 28 Three Steps Procedures

Figure 28 illustrates the three steps of this procedure.

1. Random access preamble assignment: eNodeB sets up the 6 bit preamble.
2. Random access preamble: UE forwards the assigned preamble.
3. Random access response:
 - Same procedure as contention-based
 - Sent physical downlink control channel (PDCCH) within some TTI
 - Sent initial UI grant for handover, information timing for DL data, RA-preamble
 - more than one UE may be addressed in one responses

2.7 LTE in unlicensed spectrum

Nowadays an huge number of access technologies such as WiFi (802.11), Bluetooth (802.15.1) and ZigBee (802.15.4) are used the 2.4 GHz ISM (Industrial-Scientific-Medical) and 5 GHz U-NII(Unlicensed National Information Infrastructure) bands, known as Unlicensed bands.

Although the major advantages of these technologies are low cost and simple implementation, on the other side as drawbacks there are poor spectral efficiency and low user experience quality than “licensed” technologies as LTE.

The increasing number of devices that utilize these bands represent an issue for wireless mobility because they require higher data speeds, more capacity, better spectrum utilization. Moreover, wireless spectrum is a finite resource, which force telecommunication companies to move on new sharing spectrum technologies and new band opportunities in order to satisfy the market requirements.

From 2014, Qualcomm Inc. proposed an innovative technology, LTE Advanced in unlicensed spectrum (LTE-U). The idea behind LTE-U is to extend the benefits of LTE to unlicensed spectrum, enabling mobile operators to offload data traffic onto unlicensed frequencies more efficiently and effectively. The operators that use this technology can offer a more robust and consistent mobile services with higher performances.

The possibility to move on unlicensed spectrum attracts many telecommunication companies.

Verizon, in collaboration with Alcatel-Lucent, Ericsson, Qualcomm Technologies and Samsung founded during 2014 LTE-U Forum. This organization focuses to define the technical specifications of LTE-U:

- Minimum performance necessary for LTE-U base stations and consumers.
- Coexistence specifications between different standards on 5 GHz band.

Ericsson uses the term License Assisted Access (LAA) to describe a similar technology to LTE-U, which standardization is performed by 3rd Generation Partnership Project (3GPP).

MulteFire Alliance is another organization formed in 2015 that will develop the specifications and product certification for Multefire, a new technology that combines LTE-like performances with WiFi-like deployment simplicity.

3GPP defines also LTE-WLAN aggregation (LWA) standard, which specifies another method of using LTE in unlicensed spectrum with the main advantage to don't require hardware changes to the network infrastructure equipment and mobile devices.

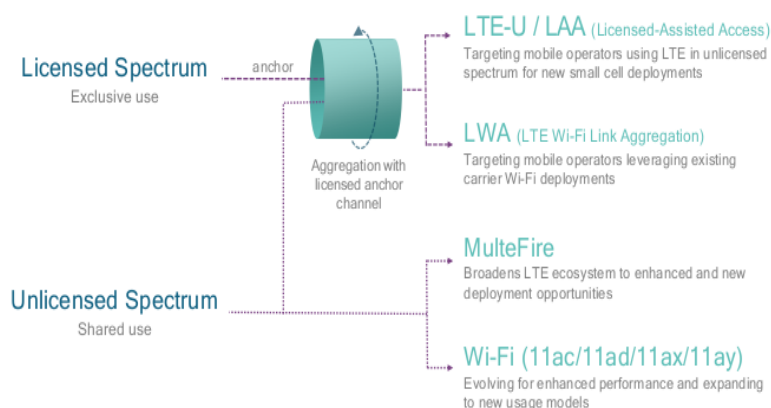


Figure 29 Carrier Aggregation Solutions

2.7.1 Band Opportunities

The Federal Communications Commission (FCC) has released different bands for commercial use, first 2.4 GHz for ISM services, then 5 GHz U-NII and recently 60 GHz millimeter-wave (mmWave) band.

In 2014, the FCC allowed to extend of another 100 MHz and 195 MHz the spectrum at 5GHz band to reach a compromise with the mobile demand and to push operators to extend their services on the unlicensed band.

Compared with the 2.4 GHz band, the 5 GHz band is less congested and used. It is mainly used from 802.11a protocol, meanwhile inside 2.4 GHz are placed cordless phones, ZigBee, Bluetooth and WiFi enabled devices.

Nowadays, lot of vendors are interested in high frequency bands (28 or 60 GHz) to achieve higher capacity. FCC in particular analyzes if the 28 GHz band should be also available for users, because up to now it is used as licensed for multipoint distribution services (LMDS).

The 60 GHz has more bandwidth opportunities than 28 GHz, but problems regarding oxygen absorption and atmospheric attenuation represent a challenge in the design of the air interfaces and physical layer.

Figure 30 shows the unlicensed spectrum overview in different countries at 5 GHz.

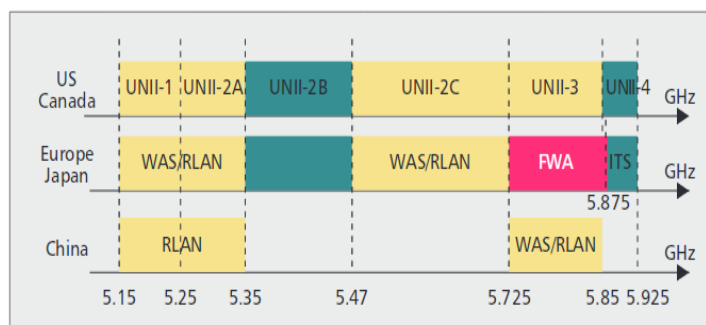


Figure 30 Frequency Occupancy

In the United States the following bands are actually used for unlicensed services:

- 5.15–5.35 GHz (UNII-1, UNII-2A),
- 5.47–5.725 GHz (UNII-2C),
- 5.725–5.85 GHz (UNII-3)

Meanwhile in Europe and Japan we have:

- 5.15–5.35 GHz
- 5.47–5.725 GHz

In the last years, European Commission allowed the unlicensed WAS (wireless access system) and RLAN (radio local area networks) to use 5.725-5.85 GHz spectrum, which

is used for intelligent transport systems and intelligent wireless access.

In China there are specific bands for indoor use only (5.15-5.35 GHz) and others for both the scenarios (5.725-5.85 GHz).

2.7.2 Design Constraints

The major constraint of unlicensed spectrum sharing is the fair coexistence between the different technologies. To guarantee this milestone, is necessary to formulate some principles and regulations regarding transmission power, radar protection, channel access methods, spectrum aggregation, etc.

2.7.3 Transmission Power

This represents the first issue to deal in the use of unlicensed spectrum.

A correct regulation of the transmission power permits to manage the interference between users; for example inside an indoor scenario, where APs work within 5.15-5.35 GHz spectrum band, the maximum transmission power is 23 dBm in Europe and 24 dBm in USA, against the 30 dBm within 5.47-5.85 GHz of an outdoor scenario.

The control of the maximum power is known as transmit power control (TPC) mechanism. TPC regulates the power level in order to avoid interference and increase battery life.

2.7.4 Radar Protection and Frequency Selection

In the list of devices that operate in 5 GHz unlicensed spectrum there are also Meteorological radar systems. To reduce interference on these devices and protect the signal, Dynamic Frequency Selection (DFS) mechanism is adopted in 5.25-5.35 GHz and 5.47-5.725 GHz.

When DFS is enable, LTE-U devices periodically monitor the presence of radar signals and will change the channel to one that is not interfering.

Moreover, there are political and geographical regulations behind DFS. In Europe and USA, unlicensed users are not allowed to access the settings of DFS functionality and in Canada users are forbidden to enter the 5.6-5.65 GHz spectrum because is used by weather radar.

2.7.5 Spectrum Aggregation

LTE in unlicensed spectrum has the same MAC protocol as LTE system. The high interference resistant performance of this protocol makes difficult the coexistence with WiFi systems, since they adopt a contention based MAC with backoff mechanism.

To guarantee fairly coexistence, the devices working with LTE unlicensed must check if

the channel is busy by other system before transmit; this procedure is known as clear channel assessment (CCA) or listen-before-talk (LBT).

Different regional requirements increase the complexity of design fair channel access systems. In Europe and Japan is required LBT access mechanism, which implies changes to the LTE air interface. In other markets such as North America, Korea and China is not required the design restrictions and access mechanism can be done according to the existing LTE Release 10-12 standards.

Channel Assessment (CA) mechanism is useful for combine different frequency bands into virtual bandwidth to improve data rates. The control plane messages as radio resource control signals and PHY layer signals are always sent on licensed band to guarantee QoS. The user plane data can be transmitted on both the type of bands.

2.7.6 LAA Scenario Configuration

LAA is an LTE technology enhancement defined in 3GPP Release 13, which is planned to work as a supplemental downlink in the 5 GHz unlicensed band, with the primary cell (Pcell) always operating in a licensed band.

The 3GPP study item (SI) regarding LTE/WiFi interworking was approved by RAN in September 2014, where the main SI goal was to define the LTE needs for operate in unlicensed spectrum friendly with WiFi.

Starting from RAN1 in Q4-14, the initial discussions were on:

1. Regulatory requirements: overview of the regulatory requirements for unlicensed operation in 5 GHz (R1-145483, sec. 4), different regional requirements (power levels, channel sensing, etc.).
2. Deployment scenarios:

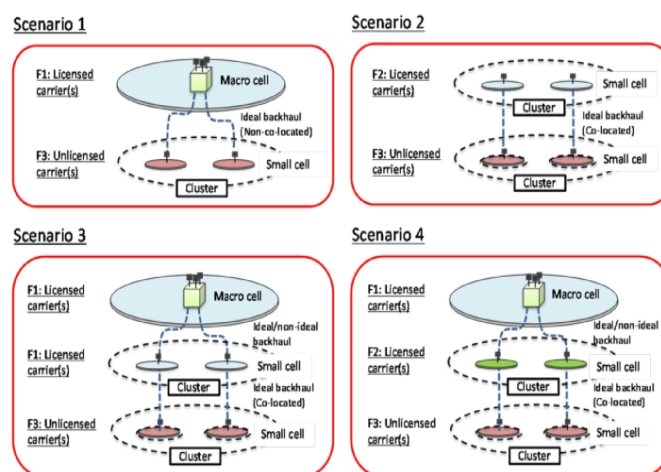


Figure 31 Scenario Deployments

Scenario 1: carrier aggregation between licensed macro cell and unlicensed small cell.

Scenario 2: carrier aggregation between licensed small cell and unlicensed small cell without macro cell coverage.

Scenario 3: licensed macro and small cell with carrier aggregation between licensed and unlicensed small cell.

Scenario 4: licensed macro cell, licensed small cell and unlicensed small cell.

3. Fair coexistence with WiFi:

- *LAA should not impact Wi-Fi services (data, video and voice services) more than an additional Wi-Fi network on the same carrier; these metrics could include throughput, latency, jitter etc.*

According to the RAN1 specifications, LAA is more suitable for small areas (indoor environment or outdoor hotspots), since in unlicensed spectrum exists power limitation constraints.

In this scenario, during a transmission, a licensed carrier called the primary component carrier (PCC), and several unlicensed carriers called secondary component carrier (SCCs), are arranged for a user.

Moreover, there are two operation modes for LTE-U:

1. supplemental downlink (SDL): the unlicensed spectrum is used only for downlink transmission, since downlink traffic is more heavier than uplink traffic. With this operation mode, the LTE eNodeB performs channel occupancy detection and other functions. Usually the applications that require this mode are for example file/music downloading, streaming online video.
2. time-division duplex (TDD): as in LTE TDD system, in this mode the unlicensed spectrum is used for both downlink and uplink. The advantage of this operating mode is the flexibility of resource allocation between downlink and uplink at the cost of more implementation complexity on the user side (LBT features, radar detection requirements, etc.). The applications that require this mode need high uplink rates such as FTP uploading and real-time video chatting.

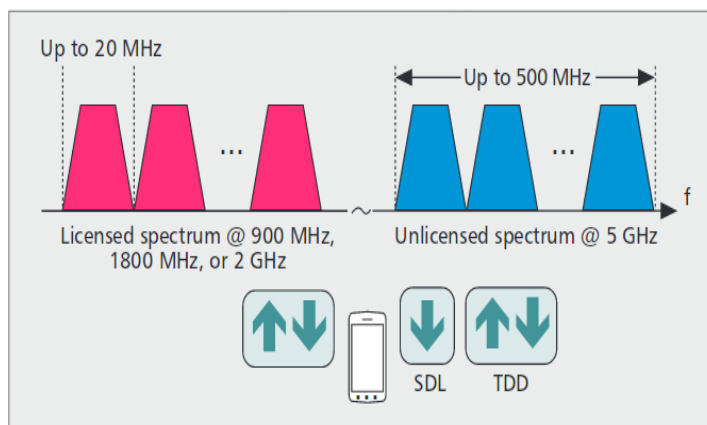


Figure 32 Frequency Division

One of the important point of LAA is to guarantee fair sharing of unlicensed spectrum with other operators and technologies. LAA implements a system where LAA node searches for a channel with low load to reduce interference with other technologies.

Moreover, LAA implements LBT feature to meet regional requirements (specified in Release 13), which is the only fairness coexistence mechanism in unlicensed spectrum. LBT is used in radio communications, where the transmitter first sense the radio environment before start the transmission. In order to operate, the devices need to find a free radio channel at a certain power threshold.

Figure 33 describes the early stages of LBT mechanism and figure 34 more in detail the clear channel assessment (CCA) and extended CCA (eCCA). In eCCA, if LAA doesn't detect a signal based on ED threshold, then go ahead with transmission, otherwise if the channel is busy, it waits for it to become clear. Once it is clear, wait a random number of CCAs indicating that the channel has been free before starting transmission.

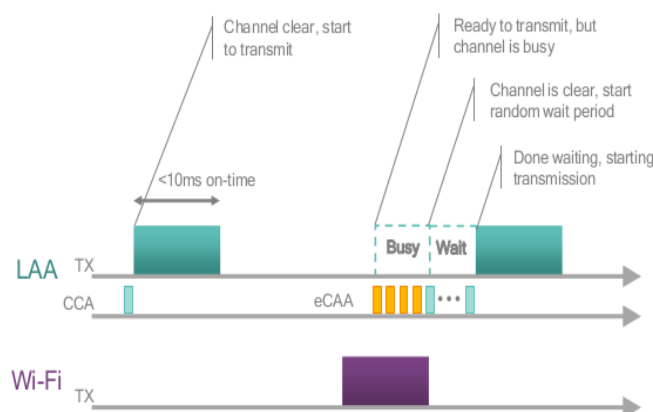


Figure 33 Listen Before Talk

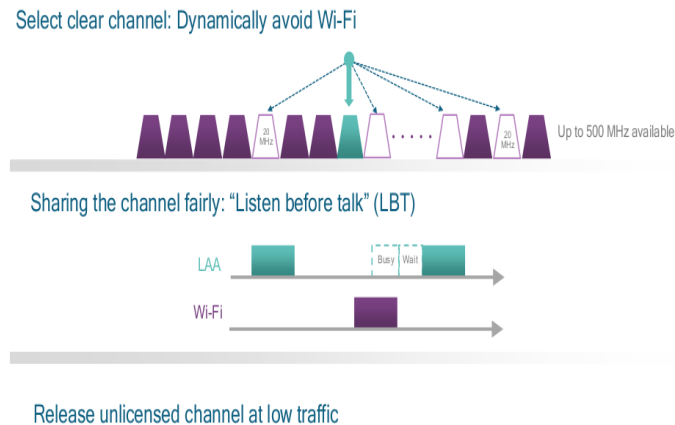


Figure 34 LBT Frequency Division

There are different LBT categories:

1. Category 1: No LBT.
2. Category 2: LBT without random back-off.
3. Category 3: LBT with random back-off with fixed size of contention window.
4. Category 4: LBT with random back-off with variable size of contention window.

3GPP decided to implement LBT category 4 for LAA mechanism.

2.7.7 LTE-U Scenario Configuration

LTE-U is another option to implement LTE in unlicensed spectrum that is created outside 3GPP.

An interesting aspect of LTE-U is that it doesn't include any LBT mechanism or regulatory requirements; this makes it suitable for such countries (USA, Korea, China) where is not mandatory to use LBT.

The fair coexistence is obtained with the following proprietary mechanisms:

1. Channel Selection: this procedure is used from eNodeB to choose the cleanest channel based on WiFi and LTE measurements. Thanks to this mechanism, the interference between eNBs and WiFi devices is eliminated.

The channel selection algorithm analyzes continuously the status of the network and if necessary will select another more suitable.

2. Carrier-Sensing Adaptive Transmission (CSAT): it is employed in very complex scenario where LTE-U nodes can share the channel with the neighboring WiFi

APs.

Usual co-channel coexistence techniques (LBT, CSMA) are focused on contention based access, where before transmitting the transmitters make sure the channel is free.

CSAT uses TDM mechanism in order to guarantee coexistence. The node senses for longer (than LBT and CSMA) duration and according to the medium load the algorithm defines LTE transmission proportionally. CSAT defines a TDM duty cycle in which the small cell sends data in the ON fraction of time, and gates OFF during the remaining time slot.

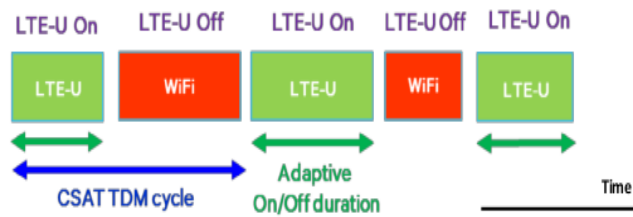


Figure 35 Duty Cycle

CSAT is similar to CSMA except for the different latency. This can be reduced by avoiding channels where WiFi APs use for discovery signals and QoS traffic (primary channels). The LTE MAC layer manages the ON-OFF states of LTE-U. The access method and duration is chosen according with UE.

Since the anchor carrier in licensed band is always available, the SDL carrier in unlicensed band can be used for opportunistic purposes. If the DL traffic on the small cell is in overload, the SDL carrier can be activated to support the offloading. When the traffic can be managed only by the primary carrier, the SDL carrier is turned off.

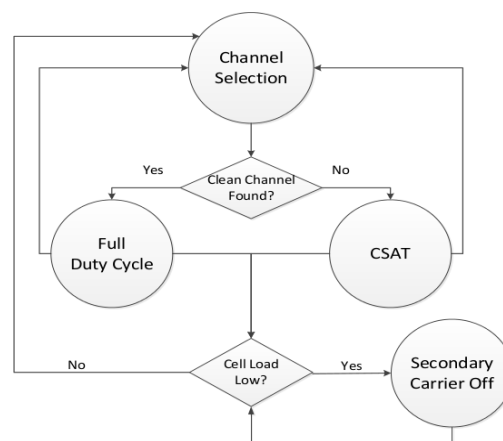


Figure 36 Channel Selection

3 The proposed coexistence mechanism

In this chapter the design choices made during the project are analyzed and justified. The following list summarizes the research steps performed:

1. In the first phase of the thesis project was fundamental to analyze which are the reasons that led the major telecommunications companies (Nokia, Qualcomm, Ericsson, ...) and organizations (3GPP, 5GPP, ...) to investigate new techniques to optimize coexistence between WiFi and LTE.

From the global context has been examined state of the art of coexistence technologies currently being tested (LAA, LTE-U, MulteFire), the advantages and disadvantages of these technologies, the characteristics that the telecommunications market requires and at the tradeoff between politician and technical reasons behind these new technologies.

2. The choice of the programming environment and language were crucial because it would influence the complexity and efficiency of the project during its development.

Two simulators were selected at the beginning: W.I.N.T.E.R group Network Simulator and Ns-3 Network Simulator.

The first is a proprietary software of W.I.N.T.E.R research group, while the latter is an open source software known worldwide.

Ns-3 was chosen because of its rich open source documentation and an already implemented module for coexistence between WiFi and LTE.

3. To become familiar with the development environment and ensure the accuracy of the results obtained with Ns-3, it has been carried out a phase of simulator calibration.

The goal was to simulate the results of the professor Giuseppe Bianchi paper: "Performance Analysis of the IEEE 802.11 Distributed Coordination Function".

Key metrics analyzed have been: throughput, bit rate, number of collision and channel collision probability.

4. After the calibration phase, were carried out the first tests of the LAA module in Ns-3.

The goal of these tests was to understand the accuracy of the results demonstrated in several publications, analyze under which conditions is respected fairness between WiFi and LTE on the same frequency, what are the benefits to integrating LTE inside the unlicensed spectrum, study Listen-before-Talk and Duty Cycle protocols for spectrum sharing, define possible approaches to optimize the use of

resources on the unlicensed spectrum.

5. Completed the investigation phase, the approach to be implemented in the algorithm for the correct spectrum sharing was defined. In this phase is realized the pseudo code that later will be implemented in our simulator.
6. Start the implementation of the algorithm in C ++ language inside Ns-3.
In this stage is defined the simulation scenario, the number of access points, the physical parameters in accordance with those established by 3GPP, simulation time, logging files and metric implementation to assess during the trials.
7. Execution of the first tests of the new algorithm. In this phase was checked stability, benefits and limitations.
The evaluation of performance is made through log files and the results obtained are compared with the theoretical ones.
Moreover, the advantages and disadvantages of the algorithm deployed for channel sharing versus Listen-before-talk are evaluated.
8. Once was approved the efficiency of the algorithm, it was started the real testing phase.
Multiple wireless traffic simulations have been performed with the support of W.I.N.T.E.R server.
During this phase, in addition to the logs files were collected data within tables to make easier the post processing phase.
9. Suggestions for future works and conclusions.

3.1 Calibration

The calibration phase was carried out by following as much as possible the model developed by Professor Bianchi.

The two main selected metrics to evaluate the performance of our simulator are: saturation throughput for increasing number of stations connected and packet collision probability on the channel.

The calibration has been performed for both techniques implemented for the transmission of packets with the 802.11 protocol: basic access mechanism and request-to-send/clear-to-send (RTS/CTS) mechanism.

The topology used within the scenario provides a single access point WiFi and a variable number of stations. The model doesn't specify the nodes position inside the environment; a static random position configuration was chosen.

The time needed from any station to detect the transmission of a packet from any other station depends on the physical layer configuration; it influences the propagation delay,

the time necessary to switch from TX to RX states and the time to transmit the channel state.

According to Bianchi's paper, there are three possible physical layer configurations:

1. Frequency Hopping Spread Spectrum (FHSS).
2. Direct Sequence Spread Spectrum (DSSS).
3. Infrared (IR).

Despite the Bianchi's results are obtained with FHSS configuration, in our project we selected DSSS configuration; this choice was made because inside Ns-3 simulator the standard 802.11b employs an easy DSSS .

As last parameter of the physical layer, Ns-3 permits to choose between two PHY layer models: YansWifiPhy and SpectrumWifiPhy. For the calibration part was selected Yans model because is the most recent and stable version developed for this simulator.

The MAC later is divided into two parts: MAC high deals with the configuration of the elements present inside the scenario (access point and stations), while MAC low controls rts/cts /data /ack transactions, implements DCF and EDCAF functions and controls the packet queue, packet fragmentation and retransmission.

The Bianchi's model does not specify in its simulations any function for the beacon generation, probing and association. To remain as faithful as possible to the Bianchi model and at the same time to a real scenario, were adopted two types of configurations: basic access mechanism has been implemented considering beacon transmission, while rts/cts mode was made using an adhoc WiFi module that does not use any form of beacons. It is necessary to point out that although both the mechanisms were tested, after the calibration phase will be mostly considered the rts/cts mode since allows to solve the hidden nodes problem and presents better performances for the transmission of large packets.

The calculation of the normalized throughput in saturation conditions was performed at the MAC layer considering the MAC header and the payload. The results are obtained by varying the number of stations connected to the access point, maintaining a simulation time of 20 seconds and performing normalization with respect to the channel rate equal to 1 Mbit/s.

The following table summarizes the parameters utilized inside the scenario.

Field	Basic access mechanism	RTS/CTS mechanism
CWmin	32	1024
CWmax	32	1024
Packet payload	3200 – 8184 bits	8184 bits
MAC header	272 bits	272 bits
PHY header	128 bits	128 bits
ACK	112 bits + PHY header	112 bits + PHY header
RTS	/	160 bits + PHY header
CTS	/	112 bits + PHY header
Channel Bit Rate	1 Mbit/s	1 Mbit/s
Propagation Delay	1 µs	1 µs
Slot Time	20 µs	20 µs
SIFS	28 µs	28 µs
DIFS	128 µs	128 µs
ACK_Timeout	300 µs	300 µs
CTS_Timeout	300 µs	300 µs
Simulation time	20 sec	20 sec

table 5 Simulator Parameters

The normalized saturated throughput formula used is:

$$\frac{(MAC\ header + Payload)}{(1000000) * (Simulation\ time)}$$

To increase the accuracy of the obtained results, for the same number of stations the simulation is executed multiple times with different seeds and runs values in order to minimize the error connected to the implicit deterministic behavior of the simulator.

Figure 37 shows the normalized saturated throughput for different number of station connected.

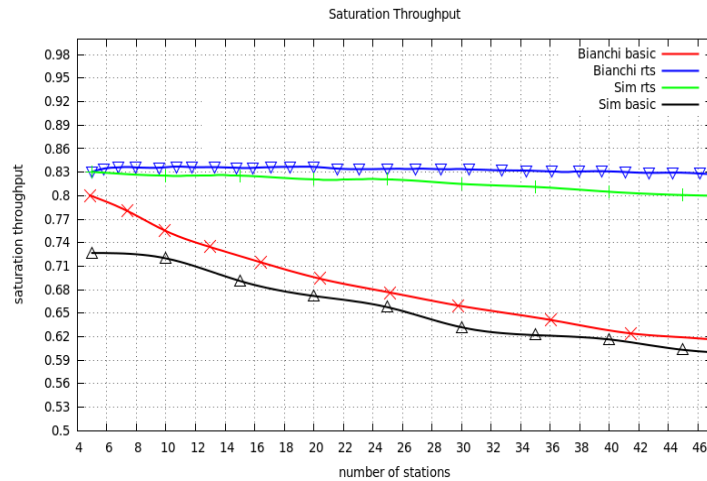


Figure 37 Ns-3 Calibration

As can be seen from the figure, our model is very accurate in the case of rts/cts mechanism with a maximum error of 0.0155 when there are 50 stations connected, while with the basic mode there is a higher error respect to the Bianchi's results.

The accuracy of the basic mode is strictly related to the packet size utilized during the simulation; the following results show how the normalized saturated throughput in basic mode is conditioned from the packet size:

- test 1: 15 stations, packet size = 572 bytes → throughput = 0.741
- test 2: 15 stations, packet size = 400 bytes → throughput = 0.691
- test 3: 45 stations, packet size = 572 bytes → throughput = 0.649
- test 4: 45 stations, packet size = 400 bytes → throughput = 0.603

From these and other tests conducted during the calibration phase is highlighted that small packet size follows better the Bianchi basic model for higher number of stations connected to the access point, meanwhile high packet size is more suitable for a small number of stations.

It is important to consider that the Bianchi's results are obtained using FHSS physical layer configuration.

The main difference between FHSS and DSSS is represented by the size of the preamble of each packet. Figure 38 shows the two different structures.

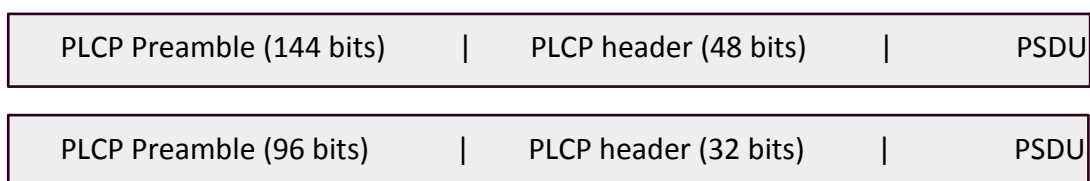


Figure 38 Frame difference between FHSS and DSSS

This size difference significantly affects the throughput calculated at link level, justifying the error between the two models as shown in the figure 37.

Once confirmed the accuracy of the simulator through saturation throughput parameter, the calibration step has been focused on the packet collisions analysis. The scenario used includes a variable number of stations that transmit to the same access point at the same frequency. For the same number of stations more tests are conducted in order to increase the randomness of the scenario and to obtain more precise values for the calculation of probabilities.

For each test, it calculates the probability of collision on the channel as:

$$\frac{\text{number of collided packets}}{\text{number of collided packets} + \text{number of packets successfully transmitted}}$$

Once obtained this probability for a number of tests between 20 to 40, the probability of collision on the channel is calculated as the average of this probability for the number of tests performed.

In figure 39 are shown the obtained results.

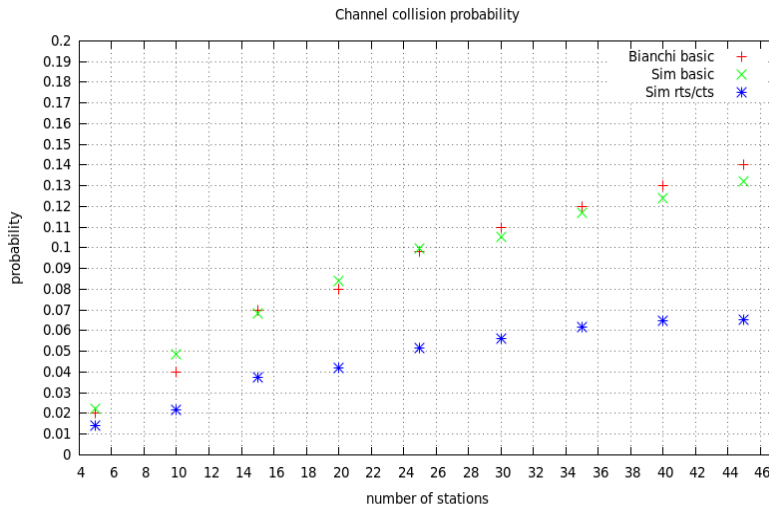


Figure 39 Ns-3 Collision Calibration

Despite the reference paper calculates the probability of collision on the channel only for the basic access mechanism, in our model we wanted to compute this probability also for the rts/cts case.

Our model follows the results obtained by Bianchi for basic access mechanism. For the rts/cts mechanism there are not data to make a comparison, but as expected it is possible to observe how the probability for this mechanism is less than the basic access method as it solves the problem of hidden nodes.

3.2 Coexistence analysis

The objective of this research phase is to define our own algorithm to improve the coexistence performances between WiFi and LTE on the unlicensed spectrum. Several tests of the LAA module implemented in Ns-3 were performed to verify if the fairness is respected as explicitly required by the 3GPP standard:

“LAA must not to impact WiFi services more than an additional WiFi network on the same carrier”

The different set of tests are conducted.

For the first set, the scenario is formed by two access points, the first WiFi and the second LAA, and two user equipment, each one of them connected to a different access point.

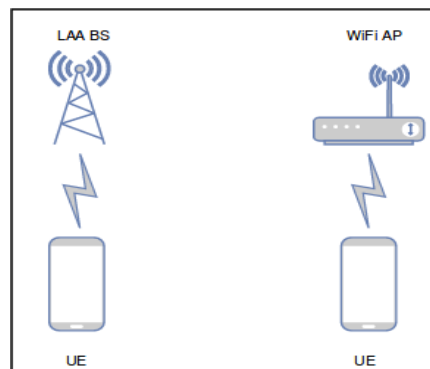


Figure 40 Scenario Configuration

Each subtest was conducted with the same simulation time. The parameters that have been changed to ensure fairness between the two technologies are:

1. Channel access manager: default(LTE), Listen-before-talk or Duty Cycle
2. LBT Transmission opportunity (TXOP): 4,8,12,16 ms
3. LAA energy threshold: -50,-72,-100 dbm
4. Duty Cycle period duration: 0, 0.5, 1
5. Content window update rule: any, nack10, nack80, all nacks

The following table shows the results in terms of throughput (Mbps) for each technology, LAA and WiFi.

Op A	Op B	Channel access manager	TX OP	LAA energy threshold	Transport protocol	DC	Content window update rule	Throughput operator A	Throughput operator B
laa	wifi	default(lte)	8	-72	udp	1	nacks80	75.0368	0
laa	wifi	lbt	16	-72	udp	1	nacks80	66.3595	7.51884
laa	wifi	lbt	12	-72	udp	1	nacks80	63.9397	9.4405
laa	wifi	lbt	8	-50	udp	1	nacks80	59.8211	12.7139
laa	wifi	lbt	8	-72	udp	1	nacks80	59.5841	13.8036
laa	wifi	lbt	8	-100	udp	1	nacks80	59.5841	13.8036
laa	wifi	lbt	8	-72	udp	1	All nacks	59.5841	13.8036
laa	wifi	lbt	8	-72	udp	1	any	59.5841	13.8036
laa	wifi	lbt	8	-72	udp	1	nacks10	59.5841	13.8036
laa	wifi	duty cycle	8	-72	udp	1	nacks80	56.2963	30.4912
laa	wifi	duty cycle	4	-72	udp	1	nacks80	56.2963	30.4912
laa	wifi	duty cycle	12	-72	udp	1	nacks80	56.2963	30.4912
laa	wifi	duty cycle	16	-72	udp	1	nacks80	56.2963	30.4912
laa	wifi	duty cycle	8	-100	udp	1	nacks80	56.2963	30.4912
laa	wifi	duty cycle	8	-50	udp	1	nacks80	56.2963	30.4912
laa	wifi	duty cycle	8	-72	udp	0	nacks80	56.2963	30.4912
laa	wifi	duty cycle	8	-72	udp	0.5	nacks80	56.2963	30.4912
laa	wifi	duty cycle	8	-72	udp	1	All nacks	56.2963	30.4912
laa	wifi	duty cycle	8	-72	udp	1	any	56.2963	30.4912
laa	wifi	duty cycle	8	-72	udp	1	nacks10	56.2963	30.4912
laa	wifi	lbt	4	-72	udp	1	nacks80	48.1286	25.0972
wifi	wifi	lbt	8	-72	udp	1	nacks80	57.4972	59.3944

Table 6 Simulations Results

Although the tested scenario is very simple and there is high load condition on the channel, we can see how LAA suppresses WiFi in every configuration.

When the scenario is composed by two WiFi operators (yellow row), we can observe that Listen-before-Talk maintains a balanced load on the channel between the two operators. The same performances are not maintained when an operator is replaced with LAA (green row); in this case, not only LAA significantly suppresses WiFi, but also there is not a

significant increase in terms of throughput.

Looking at the results, seems that the current implementation of Listen-before-Talk or the Duty Cycle for channel sharing does not provide great increases in terms of throughput and do not respect the fairness with WiFi.

A second phase of tests has been conducted to study the WiFi behavior in saturation mode for a different number of connected user equipment. The aim is to observe how are forwarded to the different types of packets along the communication channel, and calculate the percentage of channel busy for each type of packet and for only the data packets.

The scenario used is that shown in the figure 41: there are two WiFi access points connected to a variable number of user equipment, from 2 up to 10.

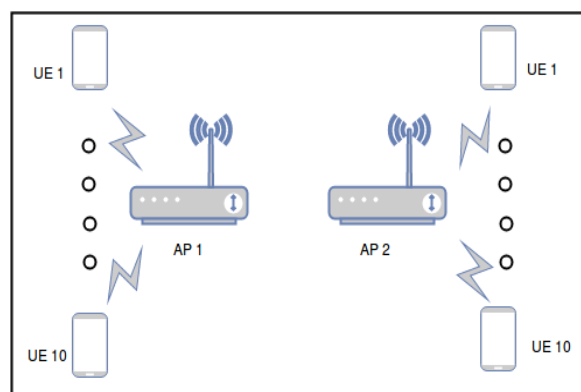


Figure 41 Scenario Configuration

3.3 Test 1

The scenario for the first test consists of 10 user equipment equally divided between the two access points.

The channel is in saturation mode and at each instant each station has a packet to send. Observing the temporal graph obtained through the pcap files extracted with the simulator (fig. 42), it is possible to have a graphical representation of the packets distribution on the communication channel.

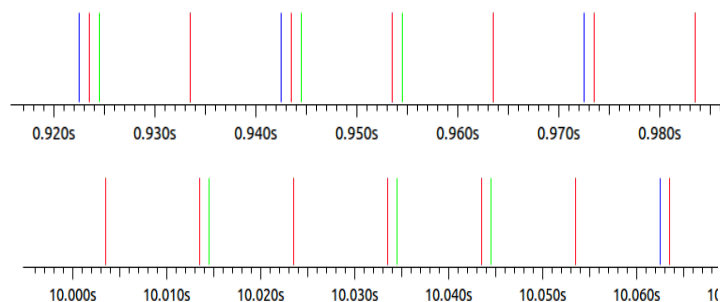


Figure 42 PCAP packets representation

3.4 Test 2

To properly carry out the communication channel management, each WiFi access point has 4 stages:

1. Receiving (RX).
2. Transmitting (TX).
3. Clear channel assessment is busy (CCA-BUSY).
4. Idle (IDLE).

The formula used for the busy channel percentage is:

$$\frac{(duration\ RX)+(duration\ TX)+(duration\ CCA-BUSY)}{2*SimulationTime}$$

The '2' factor is necessary because the parameters present in the numerator are related to both the WiFi access points.

The scenario was simulated for 2,5,7 and 10 user equipment equally divided between the two access points.

The obtained results are:

Number of stations for each AP	% of busy channel
2	98.2
5	98.6
7	98.6
10	98.7

Table 7 Test 2 Results

3.5 Test 3

The latter test considers the same scenario as test 2.

The percentage of channel busy is calculated only for the UDP packets, without considering rts, cts, ack and arp packets.

The obtained results are:

Number of stations for each AP	% of busy channel
2	96.2
5	96.9
7	94.6
10	94.5

Table 8 Test 3 Results

From the second set of tests conducted, it is possible to conclude that WiFi uses in a highly efficient way the communication channel. This makes difficult to define and design the possible benefits of introducing LTE inside the unlicensed spectrum and at the same time maintain fairness with devices that use WiFi.

After careful analysis, it was decided that our algorithm for channel sharing must respect two key points:

1. *provide a higher priority to WiFi than LTE.*
2. *ensure full quality of service to users who connect to a base station LAA.*

Looking at the latest data collected by the WiFi Alliance, the number of WiFi devices installed by the end of 2016 was greater than 6.8 billions.

For the same year, the number of LTE subscriptions worldwide was around 1.7 billions. Comparing these data with those collected from previous tests, is trivial to understand why is important to give more priority to WiFi than LTE.

Although WiFi is highly distributed globally and possesses a high efficiency on the communication channel, it is not able to guarantee the same performance in terms of throughput and QoS of a device that uses LTE.

This is the motivation of the second key point of our algorithm; it introduces the benefits of LTE on unlicensed spectrum without drastically damage the WiFi performance.

Besides these technical aspects, political aspects are also relevant. For the big telecommunications companies (Ericsson, Nokia, Huawei, ..) that operate more on licensed spectrum, the possibility to move on unlicensed spectrum is a significant increase in business opportunities.

On the other side, for those companies (Cisco, D-Link, Netgear, ..) in which the majority of their business is concentrated on the WiFi technology, the introduction of LAA is seen as an increase of possible competitors and a restriction of their business.

3.6 Coexistence solutions

A key aspect of our work from the numerous papers that deal with coexistence on unlicensed spectrum is the fact of considering an implementation that can be as easy as possible introduced in the telecommunications market.

Based on this principle, two possible operating modes are defined for the LAA and WiFi coexistence operations: User-centric Mode and Co-located WiFi/LAA Mode.

 = user that receives QoS guarantees  = user that receives no-QoS guarantees
 rt = real-time traffic nrt = non real-time traffic

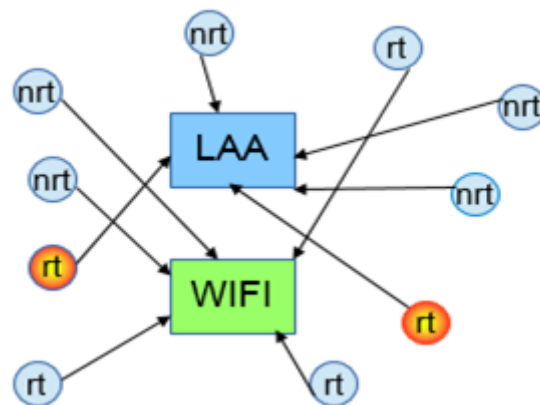


Figure 43 User Centric Mode

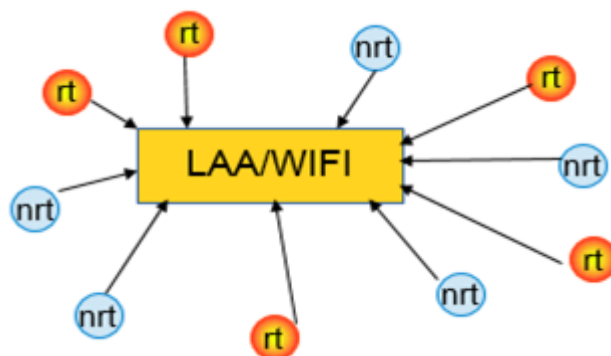


Figure 44 Co-located Mode

In the User-centric mode the LAA and WiFi base stations are two separate devices, and it is the user who decides to which technology to connect.

No type of control is possible for the WiFi access point because 802.11 standard is not modified.

When a user connects to the LAA, the base station decides to accept the user if it can guarantee QoS for the traffic type required, otherwise if there is no the minimum required resources, the connection is refused.

The resources available to ensure QoS are evaluated thanks to a the periodic analysis of the network status, the number of connected devices and the type of required traffic.

The practicality of this approach is based on the easy installation inside the scenarios where WiFi is already present and to ensure complete QoS to the users who decide to connect to the LAA BS.

The Co-located method represents a revolutionary technology for sharing the telecommunications channel between WiFi and LTE.

The two technologies are combined within a single equipment, which operates at the same time as a WiFi access point and LAA.

The basic idea of this solution is to realize an algorithm able to address the non real-time traffic only on WiFi, while maintaining LAA connected on the devices that require QoS traffic.

This approach has the great advantage to better exploit the advantages offered by both the technologies and at the same time it has a complete management of the environment.

As disadvantages is needed a complex and expensive hardware, which also includes a partial alteration of the WiFi standard.

Despite the potential of both the approaches introduced, the implementation of our algorithm has been focused on the User-centric method, as it allows a faster and cost-effective market implementation better than the Co-located method.

3.7 Channel Access Management

The channel access method is the core of our algorithm. It depends on the efficiency of allocating resources among users, the fairness between WiFi and LAA, QoS guarantees, etc.

In accordance with the two main standards (LAA and LTE-U) to aggregate LTE on the unlicensed spectrum, there are two primary methods for sharing the channel: Listen-before-talk and Duty Cycle.

Although LBT is the method chosen by 3GPP, channel sharing in our algorithm follows more the Duty Cycle approach. The simplicity in splitting the channel between WiFi and LAA combined with a dynamic allocation of resources is the strengths of our algorithm. The absence of CCA and eCCA significantly reduces signaling on the channel, and as a consequence our method presents a reduction in collisions respect to LBT.

It is important to notice that both methods do not directly consider any type of QoS to users. By correctly configuring the ON and OFF, our algorithm introduces QoS directly inside the communication channel access method.

The potential for using Duty Cycles has already been highlighted by the LTE-U forum. As an example, figure 45 shows how an appropriate ON and OFF period configuration significantly affects the load on the network.

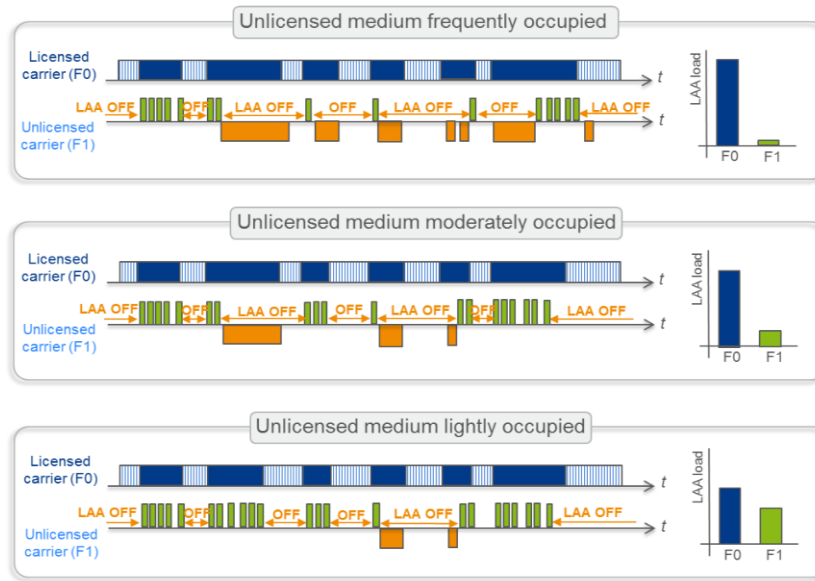


Figure 45 Different Duty Cycle Configurations

3.8 Dynamic Duty Cycle Configuration

The implementation of the two key principles are translated in the implementation of the Dynamic Duty Cycle as:

1. Fairness between WiFi and LAA → equal time resource allocation between UEs

$$\text{Allocation time for each user} = \frac{\text{Duty Cycle Period}}{\text{number of users WiFi} + \text{number of users LAA}}$$

2. guarantee QoS to real-time LAA users → respect traffic bitrate, packets interarrival time, guarantee packet delay budget.

To reduce the complexity of the simulation scenario is assumed as a hypothesis that each LAA base station knows the number of access points and user devices that use WiFi. From the point of view of a real implementation, environmental monitoring can be done with one of the following options:

1. Interception of RTS/CTS packets: usually there is a huge amount of these packets forwarded in the network. With the interception and processing of the packets headers, it is possible to have an overview of the number of devices present in the environment.
2. Interception of BEACON packets: it is possible to use a similar procedure to that explained for the frame RTS/CTS, only change the type of information contained in each packet.

3. Monitor the collisions: collision analysis is an empirical approach to have an idea of the network situation. By periodically tracking the number of collisions by counting the ack/nack or rts/cts packets, it is possible to follow backwards the Bianchi's collision model and get the number of devices that use the communication channel.

Each of these monitoring methods has advantages and disadvantages. For example, rts/cts packets are abundantly present on the channel and have a smaller size than the beacon packets, but on the other hand their interception requires a large demand of resources and energy by the LAA base stations which implies an increase of the management costs.

Our algorithm manages the resources to be shared between the users through two steps:

- Correct resource assignation to a user that is connecting.
- Reallocation of the resources when the user session is finished.

3.9 New User Arrives

In the following diagram are defined the steps performed by the LAA base station each time a user requests to connect.

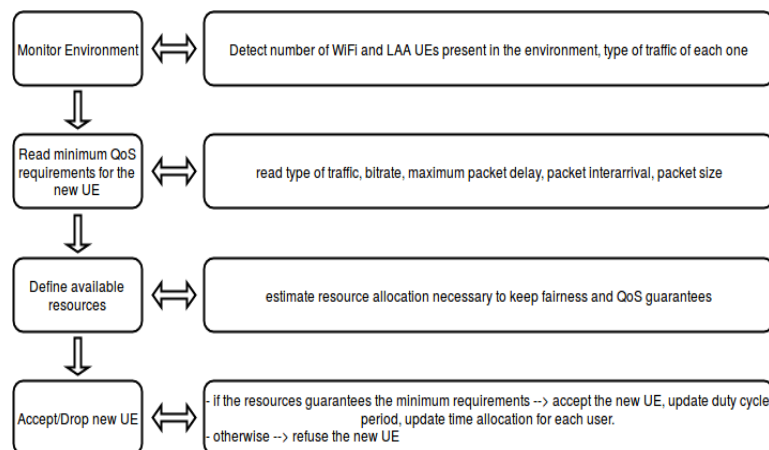


Figure 46 User arrives to the LAA BS

3.10 User Leaves

In the following diagram are defined the steps performed by the LAA base station each time a user session is over.

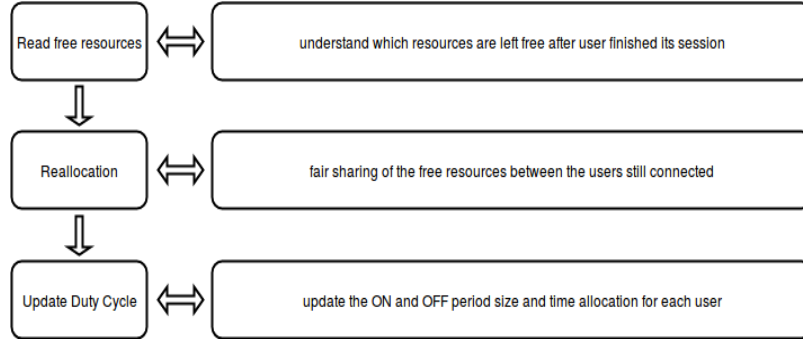


Figure 47 User completed the session

Examples

This section introduces the symbolism that will be used later in the algorithm pseudo-code. To make the mechanism more understandable, two examples are introduced. The first relates to the case that a user wants to connect to the LAA base station, and the second deals with the case of a user who has completed the service and leave the scenario.

T_{DC}	Duty cycle period (OFF LTE + ON LTE)
T_{wifi}	Time allocated for WiFi users
T_{LTE}^{NRT}	Time allocated for non real-time users
T_{LTE}^{RT}	Time allocated for real-time users

Table 9 Parameters for the Examples

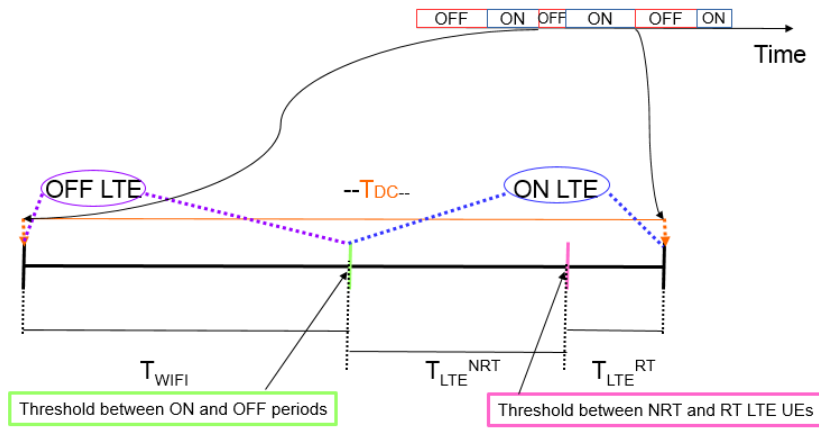


Figure 48 Dynamic Duty Cycle Variables

Example 1: UE non real-time connects to LAA BS at time T

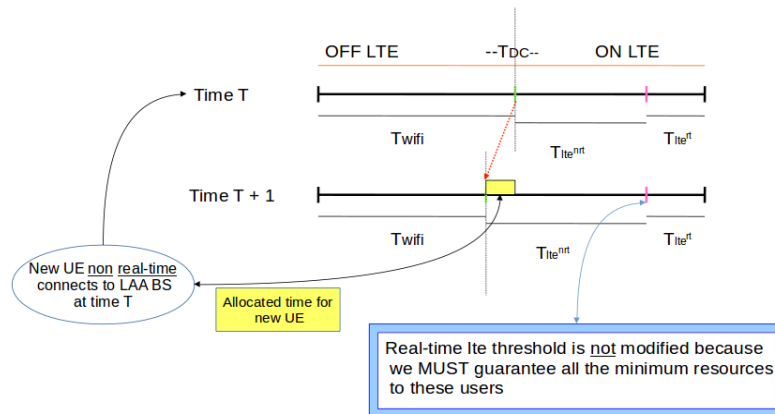


Figure 49 Example UE Accepted

Example 2: UE non real-time leaves the LAA BS at time T

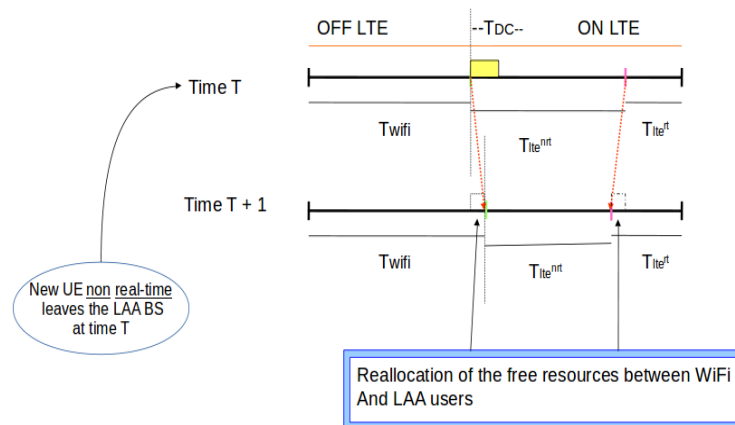


Figure 50 UE Completed the Session

3.11 Algorithm Flowchart

The channel management algorithm is divided into two main parts. The first part deals with channel access and management when a new user arrives to the LAA BS, while the second part addresses the case of the user who has completed the session and wants to leave the base station.

This section shows the corresponding flowcharts.

The following table introduces the symbolism used.

Parameter	Definition
$UE_{new}(t)$	New user equipment arrives at time t
$UE_{leave}(t)$	User equipment finished at time t the session
$n_wifi(t)$	Number of wifi users served at time t
$n_lte(t)$	Number of lte users served at time t
$PR(UE_{new}(t))$	Priority class associated to the new UE according to standardized QoS class identifiers for LTE
$Del(UE_{new}(t))$	Packet delay budget associated to the new UE
i,j	Loop indexes
T_delay	Vector containing all the packet delay budget for all the LTE users connected
T_{DC}	Duty cycle duration
$T_{wifi,lte}^{fairness}$	Slot time duration associated to each UE (wifi or lte) to guarantee fairness
$T_{ALLOCATION}^{LTE}$	ON duration
$T_{ALLOCATION}^{WIFI}$	OFF duration
T_{SLOT}^{LTE}	Estimated slot time duration for each LTE user
$T_{ALLOCATION}^{LTE}$	Estimated ON duration
$T_{NOALLOCATED}$	Unused part of Duty cycle
$T_{REALLOCATION}^{fair}$	Fair time reallocation between users
$T_{ALLOCATION}^{LTE-RT}$	Section of ON duration associated to QoS traffic users
$T_{ALLOCATION}^{LTE-NRT}$	Section of ON duration associated to non-QoS traffic users

Table 10 Pseudo-code Parameters

UE connects

See appendix 1.

UE leaves

See appendix 2.

3.12 Summary

This section explains in detail the channel algorithm implemented.

In particular, the motivations that led to the benefits of this new approach of channel

access have been assessed.

The complexity and symbology used were made more understandable with the use of different examples and with the help of the pseudo codes.

This section is also critical for understanding the choices made in the configuration of the tests in the next section.

4. Results and discussion

This section presents the results obtained from the various simulations carried out.

The main metrics used to evaluate the performance of our algorithm are:

1. Average technology throughput: the average throughput for each single technology (WiFi and LAA) is calculated based on the average UE interarrival time of the Poisson station generation process within the scenario. For each UE is calculated the throughput obtained during his service time, which will be averaged with the other UEs throughput belonging to the same technology.
2. Average packet delay: a similar process for calculating the average throughput is applied for this metric. For each user, the delay of each packet is traced from the base station to the mobile device. The average delay per packet is subsequently averaged with the rest of the UE belonging to the same technology.
3. Jain index: it represents a fairness measure or metric used in network engineering to determine whether users or applications are receiving a fair share of system resources.

$$J(x_1, x_2, \dots, x_n) = \frac{(\sum_{i=1}^n x_i)^2}{n \cdot \sum_{i=1}^n x_i^2}$$

Figure 51 Jain Index Formula

This metric in the simulations with the same type of traffic highlights how our algorithm is able to allocate resources efficiently among users.

4. Out-of-bound probability: this index indicates the percentage of packets received without respecting the maximum latency constraint for the corresponding type of traffic. Also for this metric the probability is calculated by considering the two technologies separately.

For each simulation, the collected data are represented graphically and then discussed in detail.

4.1 Simulation Scenario

The simulation environment used is the same as approved by 3GPP to evaluate LAA performance for an indoor scenario where the number of access points and mobile devices has been altered.

The two access points, WiFi and LAA, have been placed in the center of the room to ensure the higher possible coverage for all the mobile devices.

During each simulation, users enter the scenario following a precise time generated through a Poisson process.

Each user receives a static random position and keeps it until the end of his service time. To simulate different types of load on the network, each simulation is carried out for a different number of average user generated time.

To achieve the most realistic results, another Poisson process has been designed to define the service time for each user.

For each user and for each different type of traffic the service time has an average duration of 2 minutes.

The two main parameters that distinguish the simulations are the type and percentage of traffic assigned to the users that are served within the scenario.

The following two tables contain the main parameters used to configure each scenario and to each type of traffic used.

Parameter	Value
Number of Wi-Fi APs	1
Number of LAA APs	1
Network layout	Indoor scenario
System Bandwidth	20 MHz
Carrier Frequency	5 GHz
LAA Packet Scheduler	Priority Set Scheduler (PSS)
Base Station Power Tx	18 dBm
UE Power Tx	18 dBm
Path Loss Model	IEEE 802.11ax indoor model
Antenna Pattern	2D Omni-directional
Mean service duration	2 minutes
Simulation Time	1 hour
Spread UDP load	False
Wi-Fi Queue Size	> 4000000 packets (saturation mode)
MIB period	160 ms
SIB Period	160 ms
DRS Period	160 ms
DRS Enabled	True
TCP Rlc Mode	RLC AM
RLC AM Report Buffer Status Timer	20 ms
CW Update Rule	NACKS_80 %

Table 11 Scenario Configuration Parameters

Traffic	Packet Generation Interval	Packet Size	Max Packet Delay
Gaming	5 ms	50 bytes	50 ms
Video	4 ms	500 bytes	150 ms
Data	2 ms	1500 bytes	300 ms
Voice	10 ms	100 bytes	300 ms

Table 12 Traffic Parameters

The indoor scenario is shown in the figure.

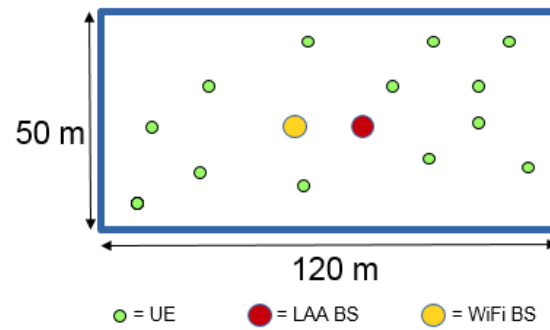


Figure 52 Scenario Scheme

4.2 Test 1: different traffic equally distributed

The following table contains the parameters that characterize the test 1.

All traffic types have been used and allocated equally among the generated users.

Parameter	Value
% of gaming traffic	25
% of video traffic	25
% of data traffic	25
% of voice traffic	25
Average station inter arrival	20,25,30,35,40,45,50,55,60 sec
Channel access management	Dynamic Duty Cycle

Table 13 Test 1 Parameters

The following charts show the results obtained. There are three main metrics used in this test: mean throughput, mean packet delay and percentage of out of bound packets.

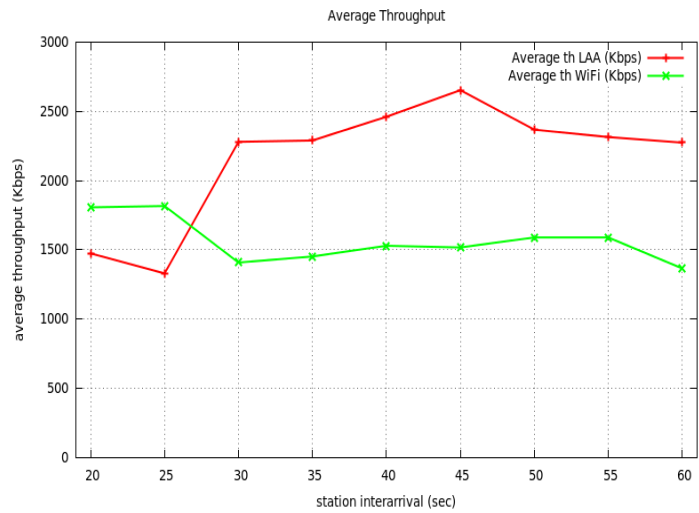


Figure 53 Average Throughput Test 1

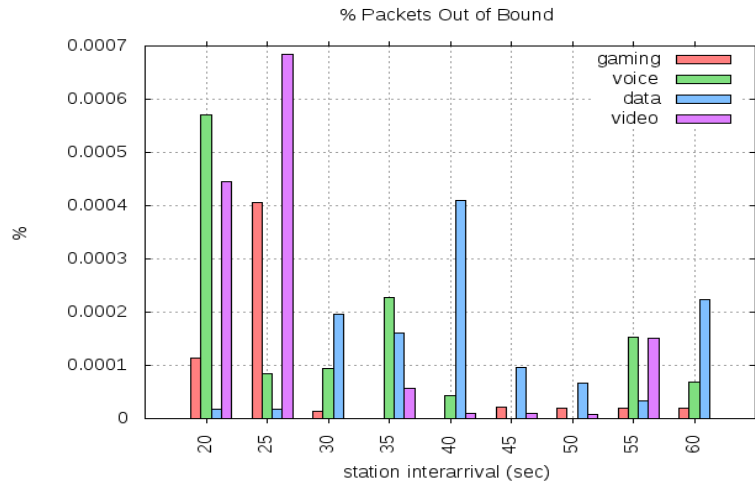


Figure 54 Average Delay Test 1

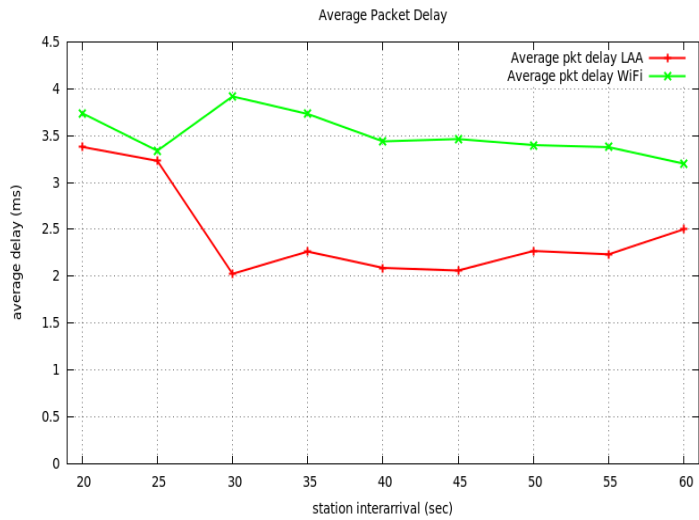


Figure 55 Packets out of Bound Test 1

results confirm that our approach succeeds in maintaining fairness between WiFi and LAA.

Analyzing the throughput it can be noticed that in the case of a highly busy channel, channel management provides WiFi priority by discarding a large number of devices that want to connect to the LAA base station.

With the increase of user interarrival time in the scenario, the whole system becomes more stable and both technologies tend to be steady and more regular.

The best performances in terms of LTE data rates can be seen in the throughput chart. Despite this trend, the number of devices served by WiFi is higher than the LAAs, and for every device of each technology is guaranteed an excellent service in terms of QoS. The second graph shows the average delay that each packet has between the mobile device and the eNodeB/WiFi AP.

As can be seen, for both technologies, the maximum delay is far below the constraints imposed by the QoS for each type of traffic.

Even with the packet delay when the interarrival station time increase, the system and the delay become more stable.

The last chart analyzes the out of bound packets index for each type of traffic.

The results obtained reflect the analytical ones, where under high traffic conditions a greater number of packets do not meet QoS restrictions.

In this case, the trend does not tend to stabilize with the increase in the interception time of the stations; This is due to the fact that the type of traffic and the location are assigned randomly to each device.

4.3 Test 2: different traffic, equally distributed, decision criteria deactivated

The following table contains the parameters that characterize the test 2.

All traffic types have been used and allocated equally among the generated users.

In this test, we want to analyze the behavior of our algorithm in the case we decide to accept any user who wants to connect to the LAA base station without considering other users' performance.

Parameter	Value
% of gaming traffic	25
% of video traffic	25
% of data traffic	25
% of voice traffic	25
Average station inter arrival	20,25,30,35,40,45,50,55,60 sec
Channel access management	Dynamic Duty Cycle, accept all UEs

Table 14 Test 2 Parameters

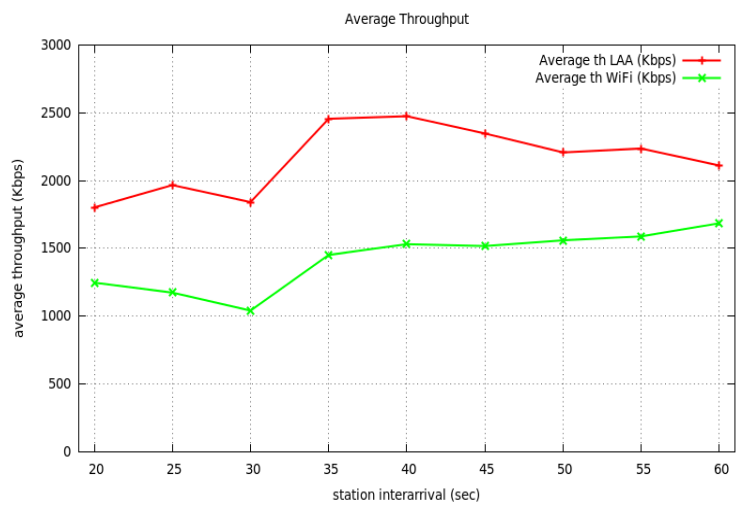


Figure 56 Average Throughput Test 2

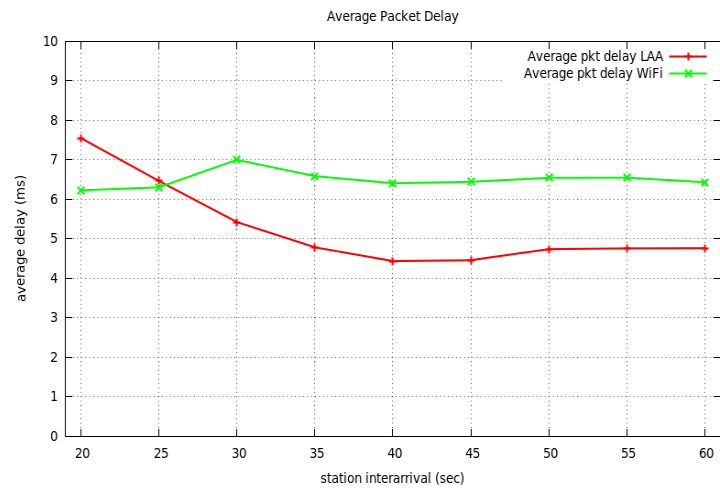


Figure 57 Average Delay Test 2

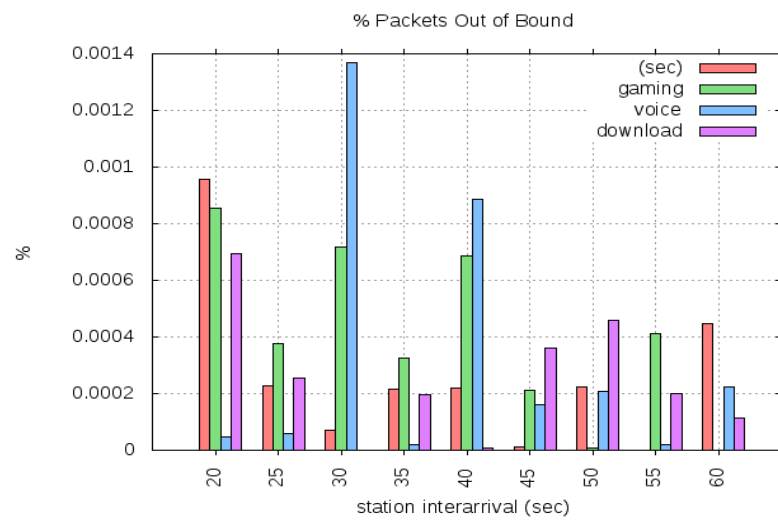


Figure 58 Packets out of Bound Test 3

Comparing the throughput chart between test 1 and 2, can be observed how a user acceptance / rejection algorithm plays a crucial role when the load on the network is high. By disabling the decision function, the LAA base station does not fully guarantee QoS to users of both technologies.

Despite this initial negative impact, the system takes a more stable impact as the interarrival time between the stations increases, following a behavior similar to the test 1. In terms of packet delay, the connection of many devices connected to LAA increases the delay at the initial stage.

Although we are accepting each user, in terms of delay we are still respecting QoS for every type of traffic. This is because the Duty Cycle is configured in accordance with the maximum package delay required in the system.

The out of bound packet chart shows an increase in the number of incorrect packets when the system is more stable.

Also in the case of an overload system there is a reduction in performance, but the overall probability of incorrect packet arrival is low and acceptable for our scenario.

The results collected in this chart do not depend directly on the type of traffic, but on the number of devices that are sending at a certain instant. More the system is overloaded, the longer is the time that a station needs before accessing the channel.

4.4 Test 3: data traffic only

The following table contains the parameters that characterize the conducted test.

In this test, only one type of traffic is assigned to all devices.

Using the same kind of traffic, an optimal metric to evaluate resource distribution among the various users is the Jain index.

Parameter	Value
% of gaming traffic	0
% of video traffic	0
% of data traffic	100
% of voice traffic	0
Average station inter arrival	20,25,30,35,40,45,50,55,60 sec
Channel access management	Dynamic Duty Cycle

Table 15 Test 3 Parameters

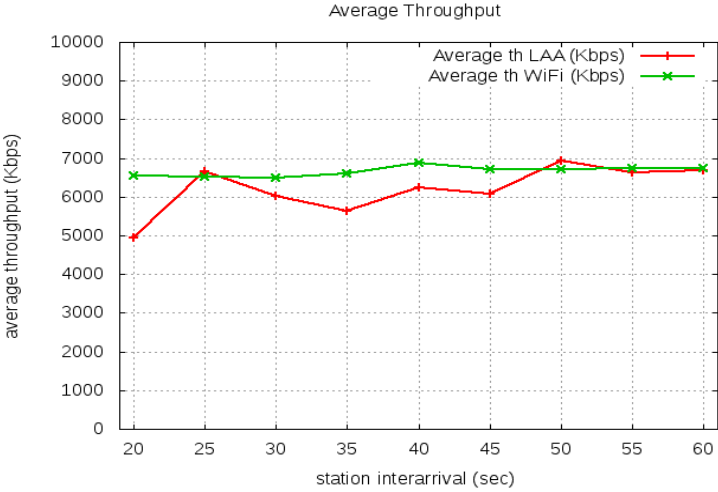


Figure 59 Average Throughput Test 3

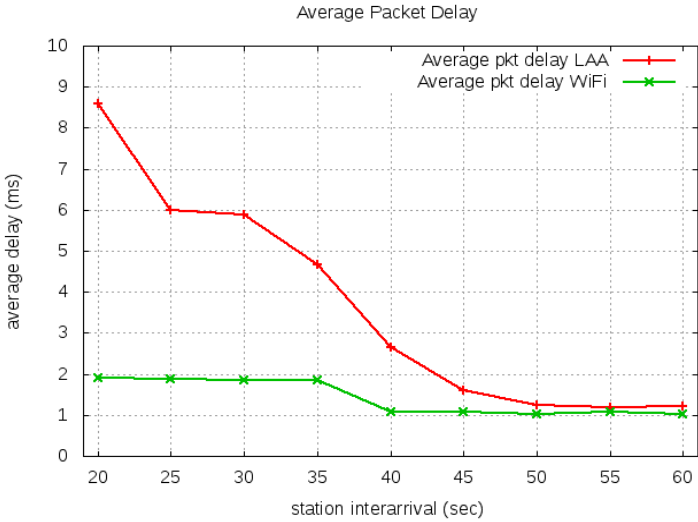


Figure 60 Average Packet Delay Test 3

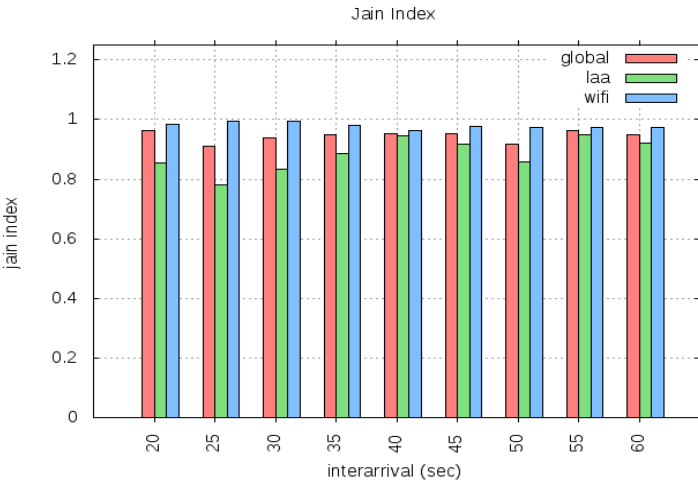


Figure 61 Jain Index Test 3

Keeping the same type of traffic through the scenario, the resources required by WiFi users are the same as those of LAA.

In terms of throughput, the ability to reject users LAA privileges WiFi technology, improving fairness between the two technologies and reducing LAA's aggressiveness to WiFi in the unlicensed spectrum.

Observing the throughput chart, can be noticed how the two curves are closer than the previous tests.

In the initial phase where many users are served, most LAA users are discarded to privilege WiFi users. As the interarrival time increases, the system stabilizes to a point where both curves tend to overlap, achieving maximum fairness between the two technologies.

The difficulty in managing the overload scenario can also be observed in the packet delay graph. In this configuration, WiFi keeps a steady trend of delay, while LAA requires the system to stabilize before reaching a WiFi-like pattern behavior.

For both technologies, the packet delay is also well below the limits imposed by QoS, ensuring a good service for all connected devices.

The last graph uses the Jain index metric to indicate how resources are divided across the users.

As you can see, in all cases the trend is close to 1, which represents the maximum efficiency in the system.

Observing the Jain index for individual technologies, can be noticed that the WiFi case is always slightly higher than the LAA, further confirming that our algorithm privileges WiFi.

4.5 Test 4: LBT vs DC

In this latest test compares the performance of our dynamic algorithm for channel access against the Listen-before-talk method.

The indoor scenario for the coexistence of WiFi and LTE already implemented in ns-3 does not provide the dynamic generation of users following a Poisson process.

For a comparison of the two techniques as realistic as possible, both scenarios were simulated under channel overload condition, following the parameters in the tables below.

Parameter LBT	WiFi	LAA
Traffic type	Data	Data
Simulation time	10 min	10 min
UEs	20	20
UEs generation	Simulation starts	Simulation starts

Table 16 Test 4 Parameters

Parameters Dynamic DC	WiFi	LAA
Traffic type	Data	Data
Simulation time	1 hour	1 hour
UEs generation	Poisson process, lambda = 20 sec	Poisson process, lambda = 20 sec

Table 17 Scenario Test 4 Parameters

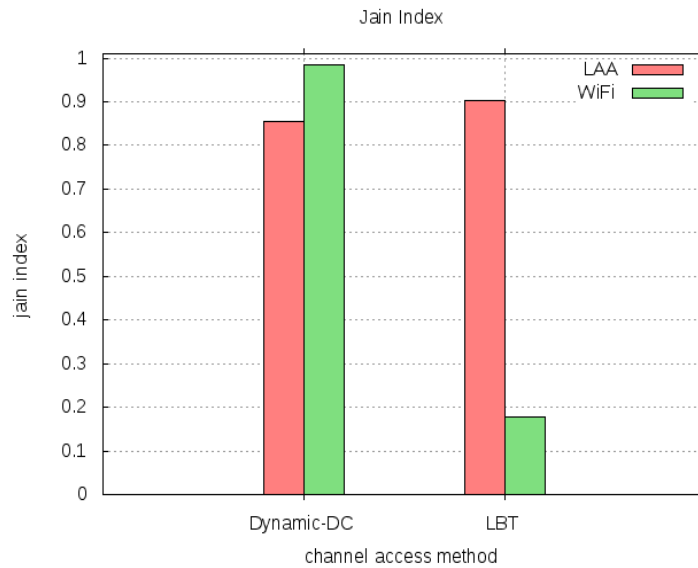


Figure 62 Jain Index Test 4

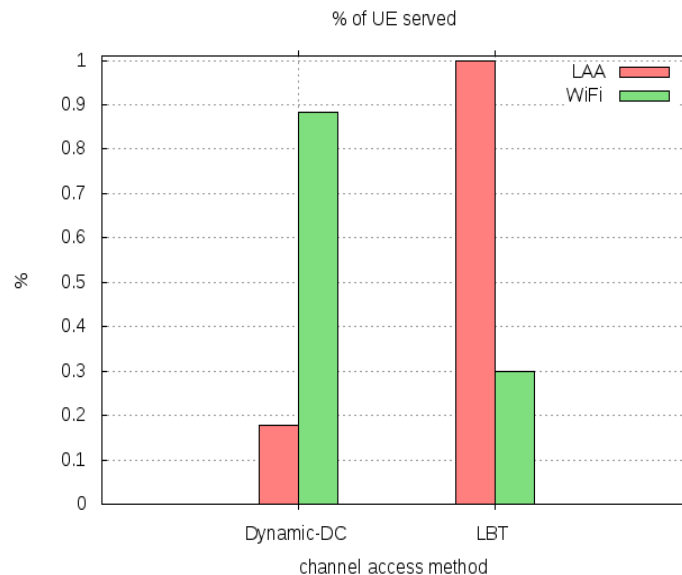


Figure 63 Percentage of Users Served Test 4

Using the same type of traffic, a good metric to test the two techniques is represented by the Jain index.

As it can be seen, the discarding of a large number of devices by the LAA base station allows a greater resources balancing between WiFi and LAA.

On the other hand, LBT cannot refuse any kind of device, highlighting LTE's aggressiveness for channel access.

Following our approach, we guarantee full QoS to all users of both technologies, always giving priority to WiFi.

In the case of LBT, resources are not evenly divided into high traffic conditions on the network, not allowing some WiFi devices to access the channel throughout the simulation time.

The inability to transmit to the channel by some devices is visible in the second graph, where the percentage of users served compared to those in the scenario is highlighted.

Looking at the dynamic duty cycle channel access results, is possible to see how on a non-licensed spectrum it is necessary to discard a large number of LTE devices to ensure fairness with WiFi and achieve good performance.

Listen-before-Talk ensures that all LTE devices transmit to the channel, keeping it busy much of the time making it difficult to access WiFi devices.

This latest test highlights the complexity of maintaining a balanced relationship between LTE and WiFi on the unlicensed spectrum.

4.6 Discussion

Continued global expansion, the transition to 5G and the idea of a world where different types of devices are able to exchange information, act and communicate is a continue challenge for telecommunications companies and standardization groups.

The development of new modulation techniques, new protocols and advanced hardware structures have allowed in recent years to consider new frequency bands for data transmission.

To make the most of these new resources efficiently and efficiently, the scientific community is carefully defining the rules for assigning and using the new frequencies correctly between different technologies.

A possible standardization method by 3GPP is Licensed-Assisted Access (LAA), which studies how to correctly gain access to the WiFi / LTE communication channel on the licensed spectrum, particularly at 5GHz.

The method developed in this Master Thesis project focuses to optimize one of the current channel access techniques by trying to reduce the aggressive nature of LTE for channel access compared to other technologies currently on the market.

According to the tests we conducted at the initial stage of the project, Listen-before-Talk, the current 3GPP-defined method for channel access, can guarantee fair coexistence between WiFi and LTE only in specific deployment scenarios. In addition, the standard does not provide any quality control of the service offered (QoS) to the customer, which is managed directly by any technology.

Correct channel sharing and more accurate control of the service offered to customers are the basis ideas for our channel access technique.

The results obtained show that our algorithm is fully able to divide and allocate resources

well between WiFi and LTE while maintaining access to the fair channel.

Quality service management techniques already implemented within the LTE standard have been further refined, taking into account the type of routed traffic when is necessary to configure LTE and WiFi access periods.

The results show how achieving a simple and low-cost solution to introduce LTE on the unlicensed spectrum requires connections control and prioritization based on network load. This significantly reduce cases where the network is in overloaded situations, guaranteeing optimal QoS to users served and less invasive impact on the channel.

The decision to define a balanced approach between WiFi and LTE was also designed to ensure equal opportunities between different telecommunications companies. In this way, companies with a strong interest in WiFi (Cisco, Broadcom, Cablelabs, ...) can compete fairly for resource sharing with LTE-oriented (Nokia, Ericsson, Qualcomm, ...).

This research has shown the importance in the next future of a proper sharing of the frequency spectrum to ensure the development and coexistence of new technologies.

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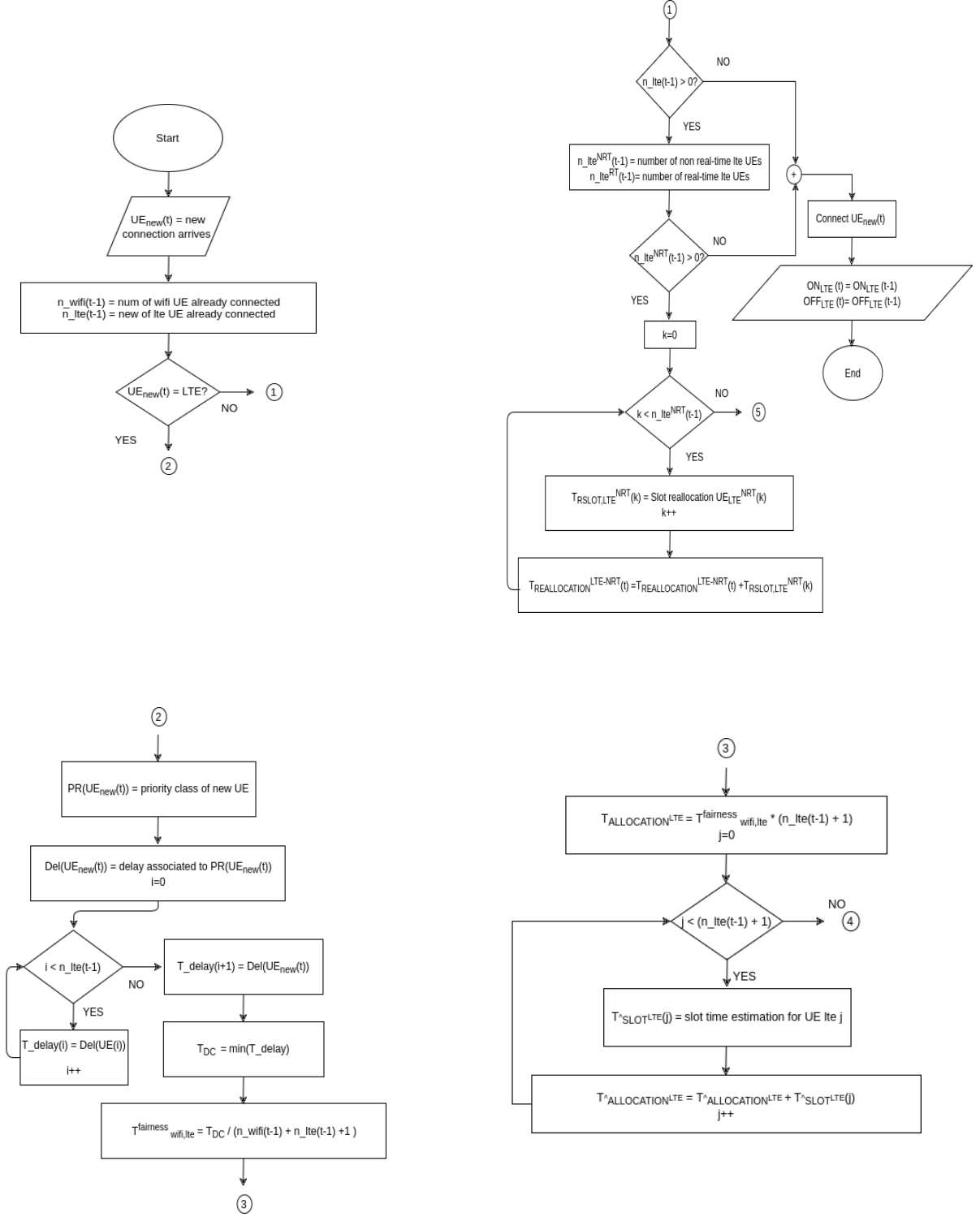
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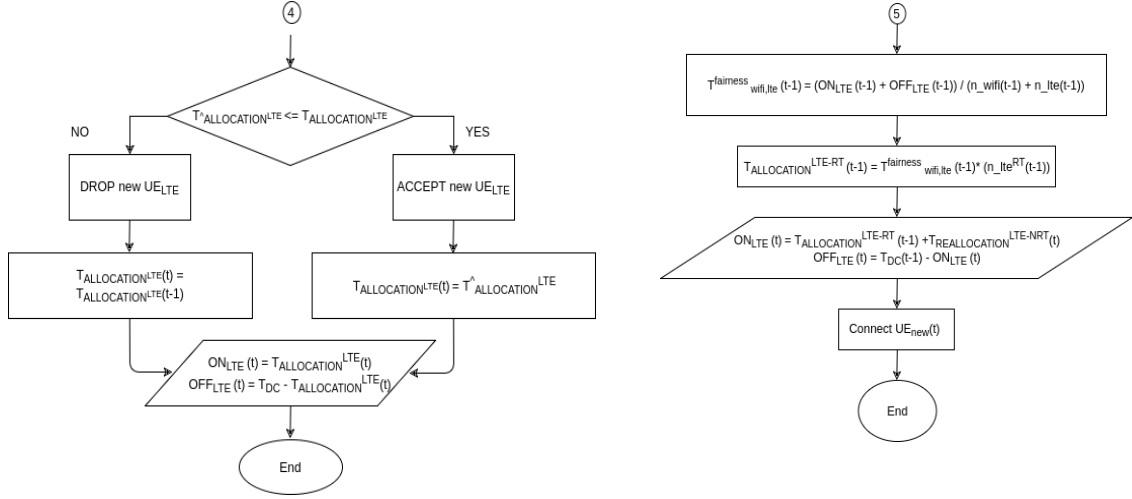
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6. Appendix

1) Flowchart UE connects





2) Flowchart UE leaves

